

# A Journey Through Quantized Space: Toward a Theory of Everything

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## Cassiopeia's ToE

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If space can be bent, then it must have structure!

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# Foreword

## 0.1 Reconciling Quantum Field Theory and General Relativity

Physics has long operated on two pillars: **Quantum Field Theory (QFT)**, which describes the interactions of particles and forces, and **General Relativity (GR)**, which governs the behavior of spacetime and gravity. Both theories have been experimentally validated to extraordinary precision, yet they remain fundamentally incompatible at the deepest levels. This work does not propose an alternative to these frameworks but rather seeks to uncover the deeper foundation from which both QFT and GR emerge naturally.

### Why Quantum Foam?

It is widely recognized that the continuum nature of spacetime assumed in GR is unlikely to persist at the Planck scale ( $\ell_P \sim 10^{-35}$  m). The quantum vacuum is anything but empty; it fluctuates, generates virtual particles, and possesses measurable energy. **Quantum foam**—first suggested by John Wheeler—is the natural consequence of these fluctuations, where spacetime itself is not a fixed stage but a dynamic, probabilistic entity.

If spacetime is quantized, we must ask: *What is it made of?* The Foam-Plexus model proposes that spacetime consists of discrete quanta connected via fluctuating threadlike connections which we will call **wormholes**. These connections form dynamic fishnet-style networks which we will call a **plexus**. And gradients in the shapes of these plexuses manifest as the fundamental forces of nature. To deal with these wormholes and plexuses, we apply statistical mechanics to the quantum foam, and the result is a statistical-mechanical picture of spacetime, where its apparent smoothness at macroscopic scales arises from an underlying thermodynamic system.

### Do We Need a Lattice of Space Quanta?

A natural question arises: should we imagine spacetime as a fixed *matrix of sites* (cells of volume  $\ell_P^3$ ) connected by wormholes, or should we take the wormholes themselves as the true quanta of spacetime?

Both viewpoints are consistent with the Foam-Plexus framework:

- **Matrix picture:** one postulates Planck-scale “sites” and lets wormholes connect them. This provides a clean bookkeeping scheme and makes statistical mechanics look like a lattice gas or spin-glass model.
- **Wormhole picture:** one drops the background lattice entirely. The wormholes themselves *are* the quanta of spacetime. Connectivity defines distance; there is no hidden grid. This avoids the appearance of a preferred frame.

For physical predictions, the two pictures are equivalent after coarse-graining. Once we pass to densities and order parameters, both recover the same continuum actions (Einstein gravity, Maxwell/Yang–Mills fields, Higgs sector). The only universal restriction is a minimum wormhole length  $L \geq \ell_P$ , which provides the ultraviolet cutoff.

Thus, while the lattice picture is a useful pedagogical analogy, the Foam-Plexus model does not require it. Wormholes themselves can be treated as the fundamental quanta of spacetime, and the recovery of modern physics is unaffected.

### An Emergent Framework, Not a Replacement

A common critique of alternative theories is that they attempt to discard or replace established physics. The Foam-Plexus model does neither. Instead, it preserves **all known results** of QFT and GR while providing a deeper, more fundamental understanding of why these frameworks work.

- **QFT remains valid:** The known quantum fields – electromagnetic, weak, strong, and Higgs – exist, but they arise as emergent properties of the Quantum Foam.

- **GR remains valid:** The metric structure of spacetime and Einstein’s field equations hold true at macroscopic scales. However, the geometry of spacetime itself is **not fundamental** but instead arises from the statistical behavior of the quantum foam.
- **No preferred frame:** While space is discrete at the smallest scales, Lorentz invariance emerges naturally as a statistical equilibrium property.
- **All of classical physics was ‘correct’ too:** Newtonian mechanics is not wrong – it is simply the low-energy limit of relativity. Likewise, QFT and GR are not incorrect; they are *approximations* of a more fundamental, discrete spacetime framework.

## Why This Matters

By shifting the perspective from assuming spacetime as a continuous and differentiable entity to one where it is a thermodynamic system of discrete quanta, we open new pathways for understanding:

- The quantum origins of gravity.
- The nature of dark matter and dark energy.
- The unification of forces as statistical properties of spacetime itself.
- Possible experimental signatures in high-energy physics and gravitational wave observations.

The following sections develop this framework rigorously, beginning with the foundational principles of a quantized spacetime. Each step builds upon known physics, preserving all established experimental results while offering a deeper theoretical foundation. This approach is not merely speculative – it is **necessary** to resolve the inconsistencies between quantum mechanics and relativity.

**We do not discard modern physics; we seek to explain why it works.**

Part I

**FOUNDATIONS**

# 1 Quantum Foam Is Fundamental

## 1.1 Overview

This chapter lays out the *foundational* picture: spacetime is not a smooth continuum but a statistical ensemble of Planck-scale quanta connected by transient wormholes. From this substrate, classical geometry, Lorentz invariance, gauge fields, and the statistical basis for motion *emerge*. The aim is not to replace quantum field theory (QFT) or general relativity (GR), but to *explain* why they work so well: both appear as coarse-grained limits of the same underlying thermodynamic network.

- **Spacetime is statistical:** distances are undefined unless two quanta are connected by a wormhole. A minimum link length  $L_w \geq \ell_P$  sets a natural ultraviolet cutoff, so the *maximum possible connectivity density* is of order  $N_{\max} \sim \ell_P^{-3} \sim 10^{99} \text{ cm}^{-3}$ . This is an upper bound on link density. The actual density is determined dynamically by creation, dwell, and absorption processes in the foam.
- **Wormholes fluctuate:** lengths, orientations, and occupancies fluctuate as in a grand-canonical ensemble. Each link behaves as a quantum harmonic oscillator with a frequency set by its length and its *plexus type*.
- **Coarse-graining produces fields:** averaging over the microscopic ensemble yields smooth “order parameters” and effective free energies. In the infrared (IR), these become the Einstein–Hilbert term for gravity and Maxwell/Yang–Mills/Higgs terms for gauge/matter.
- **GR exterior recovers exactly:** outside compact sources the exterior geometry reduces to the GR vacuum. Foam corrections live in the UV/interior (core regularization, near-horizon microphysics).
- **No fine-tuning:** observable constants (e.g.,  $G$ ,  $\epsilon_0$ ,  $\mu_0$ ,  $g_{\text{YM}}$ ,  $v$ ) are *susceptibilities* of the foam—calibration-by-definition from micro-parameters, not after-the-fact tuning.

## 1.2 Quantum Foam: Spacetime at the Planck Scale

### 1.2.1 Spacetime as a Statistical Mechanical System

Spacetime consists of Planck-scale quanta linked by transient wormholes. Distances exist only along wormholes; without a connecting wormhole, separation is undefined. A minimum length  $L_w \geq \ell_P$  imposes a UV cutoff and bounds connectivity. Wormholes are created/annihilated and reoriented stochastically, so the foam is described by a grand-canonical ensemble at an effective temperature  $T$ .

**One master partition, explained once.** We classify wormholes into *plexus types*  $\alpha \in \{\text{grav}, \text{EM}, \text{weak}, \text{strong}, \text{H}\}$ . Each link is a harmonic oscillator with frequency  $\omega_\alpha(L)$  depending on its length  $L$  and type  $\alpha$ . The total (grand-canonical) partition function is

$$Z_{\text{foam}} = \sum_{\{N_\alpha\}} \prod_{\alpha} \left[ \sum_{N_\alpha=0}^{\infty} \frac{z_\alpha^{N_\alpha}}{N_\alpha!} \prod_{i=1}^{N_\alpha} \int dL d\Omega \pi_\alpha(L, \Omega) \frac{e^{-\frac{\beta \hbar}{2} \omega_\alpha(L)}}{1 - e^{-\beta \hbar \omega_\alpha(L)}} \right] \times \left\langle e^{-\beta H_{\text{cross}}} \right\rangle \quad (1.1)$$

with:

- $z_\alpha = e^{\beta \mu_\alpha}$ : a weight factor controlled by the chemical potential  $\mu_\alpha$ . It regulates how easily wormholes of type  $\alpha$  are created or destroyed, i.e. it biases the average number of wormholes in that plexus sector.
- $\pi_\alpha(L, \Omega)$ : normalized prior over lengths  $L$  and orientations  $\Omega$  (encodes stiffness, cutoffs, anisotropies).
- $\omega_\alpha(L)$ : oscillator frequency for a link of type  $\alpha$  and length  $L$  (UV stiffening as  $L \rightarrow \ell_P$ ).
- $\beta = 1/k_B T$ : inverse effective temperature of the link ensemble.
- $H_{\text{cross}}$ : inter-plexus couplings (universality of gravity, symmetry breaking, etc.); the brackets denote averaging over the factorized sector measures when uncoupled.

The harmonic-oscillator sum  $\sum_{n \geq 0} e^{-\beta(n + \frac{1}{2})\hbar\omega} = [2 \sinh(\beta \hbar \omega / 2)]^{-1}$  is already absorbed in (1.1).

**From microstates to fields: the coarse-graining map.** Define coarse fields (order parameters) per plexus:

$\rho_\alpha(x)$  (coarse link density),  $\Psi_{\text{EM}}(x)$  (complex EM order parameter),  $\mathbf{n}_w(x)$  (weak director),  $\Phi_H(x)$  (Higgs-like scalar).

Integrating out  $L, \Omega$  and the oscillator levels yields an effective free-energy functional

$$Z_{\text{eff}} = \int \prod_{\alpha} \mathcal{D}\Phi_{\alpha} \exp \left[ -\beta \int d^4x \left( \sum_{\alpha} \mathcal{F}_{\alpha}[\Phi_{\alpha}] + \mathcal{F}_{\text{cross}}[\{\Phi_{\alpha}\}] \right) \right], \quad (1.2)$$

where each  $\mathcal{F}_{\alpha} = \frac{1}{2} K_{\alpha} \Xi_{\alpha}(\partial\Phi_{\alpha}) + V_{\alpha}(\Phi_{\alpha})$  contains a gradient “stiffness”  $K_{\alpha}$  and a sector potential  $V_{\alpha}$ . In the IR, these functionals reduce to the familiar continuum actions; their couplings are *susceptibilities* of the foam:

$$G^{-1} \sim K_{\text{grav}} \chi_g, \quad (\epsilon_0^{-1}, \mu_0^{-1}) \sim K_{\text{EM}} \chi_{\text{EM}}, \quad g_{\text{YM}} \sim \chi_{\text{strong}}, \quad v = \sqrt{2} \langle |\Phi_H| \rangle, \dots$$

No parameter is “put in by hand” at the continuum level; each is determined by  $\{\mu_{\alpha}, \pi_{\alpha}, \omega_{\alpha}, K_{\alpha}\}$ .

### 1.3 Wormholes are Harmonic Oscillators

We extend the Wormhole Plexus (Foam-Plexus) model of quantized spacetime by postulating that each microscopic wormhole acts as a harmonic oscillator. This assumption introduces natural energy quantization, oscillator stability conditions, resonance constraints, and thermal/statistical consequences. We demonstrate that this oscillator structure gives rise to discrete force carriers, stable spacetime geometries, and a new interpretation of quantum entanglement as synchronized oscillator modes. The framework yields a unified foundation for field quantization, Planck-scale discreteness, and emergent geometry, while preserving Lorentz invariance and recovering known predictions of quantum field theory and general relativity. This model unifies quantum gravity and field theory, offering testable predictions for vacuum energy and entanglement

### 1.4 Introduction

In prior works, we have described the spacetime foam as a dynamic network of microscopic wormholes connecting discrete spacetime quanta. The concept of multiple overlapping networks – called Plexuses – was introduced to account for the different fundamental forces: gravity, electromagnetism, weak, strong, and Higgs. Each Plexus arises from a different type of perimeter flow on possible particle topologies, producing force-specific wormholes that form dynamic field structures. Unlike string theory’s extra dimensions or loop quantum gravity’s spin networks, the Wormhole Plexus model uses a quantized spacetime foam. Here, we propose a new refinement: each wormhole in the foam is a harmonic oscillator. This assumption has multiple consequences:

- It provides an intrinsic mechanism for energy quantization at the Planck scale.
- It stabilizes wormhole formation and decay.
- It leads to resonance criteria governing force transmission.
- It suggests entanglement as synchronized oscillation between spatially separated wormholes.

We now develop the formal and conceptual consequences of this oscillator-based Foam-Plexus structure.

### 1.5 Wormholes as Harmonic Oscillators

Let each wormhole have a natural frequency  $\omega_0$ , and be governed by a quantum harmonic oscillator Hamiltonian:

$$H = \hbar\omega_0 \left( n + \frac{1}{2} \right), \quad n \in \mathbb{N}_0 \quad (1.3)$$

The energy stored in each wormhole loop is quantized, preventing unbounded energy contributions and resolving the UV divergence problems of traditional QFT. This forms the basis of both field quantization and gravity regularization in the Foam-Plexus model.

### 1.5.1 Spatial Embedding and Stiffness

Each wormhole connects two spatial nodes separated by a minimum Planck-scale distance  $\ell_P$ , acting like a spring between spacetime quanta. We define an effective spring constant  $k$  for the wormhole in terms of its zero-point energy:

$$\frac{1}{2}k\ell_P^2 = \frac{1}{2}\hbar\omega_0 \quad \Rightarrow \quad k = \frac{\hbar\omega_0}{\ell_P^2} \quad (1.4)$$

This spring constant reflects the geometric stiffness of spacetime. Fluctuations in wormhole length manifest as curvature, with accumulated deviations producing emergent gravitational dynamics.

### 1.5.2 Longitudinal-Only Oscillations

In conventional quantum field theory and string theory, fields or strings are embedded in a higher-dimensional spacetime, allowing for transverse oscillations relative to a fixed spatial background. By contrast, in the Wormhole Plexus framework, wormholes *are* spacetime. There is no pre-existing spatial manifold in which to oscillate transversely. The wormhole itself defines the only available dimension of oscillation—the line between two connected quanta. Therefore, all oscillator modes are inherently **longitudinal**, propagating fluctuations **along** the wormhole’s axis.

This distinction has significant implications. Longitudinal oscillations support scalar and compressive dynamics, aligning with gravitational and inertial effects. They do not radiate energy as transverse electromagnetic waves do, and they contribute to emergent geometry and field quantization through stochastic reconfiguration of connection lengths, not through wave-like vibrations in a medium.

### 1.5.3 Dual Sources of Curvature: Density and Oscillator Length

In the original Foam-Plexus model, gravitational curvature emerged from statistical gradients in the *density* of wormholes in the gravity-specific Plexus. More wormholes per unit volume between regions produced stronger spacetime binding—effectively shortening distances—while fewer connections led to effective expansion. This provided a topological foundation for curvature based on network architecture alone.

The harmonic oscillator refinement adds a complementary geometric mechanism: *fluctuations in the length* of each individual wormhole. As wormholes dynamically oscillate around their equilibrium length, they introduce local expansions or contractions of space. These length changes are governed by oscillator energy states and contribute directly to the bending of geodesics.

Together, these mechanisms—wormhole density and oscillator-driven length deviation—form a unified origin for spacetime curvature. Statistical averages over both effects yield the emergent geometry we interpret as gravity. This layered approach allows the model to reproduce the Einstein field equations while offering novel predictions tied to oscillator behavior and resonance structures in spacetime.

## 1.6 Thermal and Statistical Behavior

If the wormhole network is viewed as a statistical ensemble of oscillators, it naturally obeys Planckian thermal statistics:

$$\langle E \rangle = \sum_n \hbar\omega_0 \left( n + \frac{1}{2} \right) \frac{e^{-\beta\hbar\omega_0(n+1/2)}}{Z}, \quad (1.5)$$

with partition function:

$$Z = \sum_n e^{-\beta\hbar\omega_0(n+1/2)} = \frac{e^{-\beta\hbar\omega_0/2}}{1 - e^{-\beta\hbar\omega_0}}. \quad (1.6)$$

This thermal behavior connects cosmological vacuum energy to statistical oscillator modes and imposes a cutoff on high-energy fluctuations. These statistics predict deviations in cosmological vacuum energy, potentially testable via CMB anomalies with instruments like the Simons Observatory.

## 1.7 Oscillator Modes and Fundamental Plexus Lengths

Each Plexus—gravity, electromagnetic, weak, strong, and Higgs—is associated with a distinct family of wormholes. These wormholes differ not only by their connectivity rules and coupling to particle

perimeters, but also by their preferred oscillator mode. This mode determines both the natural frequency and the equilibrium length of the wormhole within that Plexus.

We propose that the harmonic oscillator associated with each wormhole supports a characteristic frequency  $\omega_i$ , corresponding to its Plexus  $i$ . From this, a preferred length scale  $\ell_i$  emerges:

$$\ell_i = \sqrt{\frac{\hbar}{k_i \omega_i}} = \frac{\ell_P}{\sqrt{n_i}} \quad (1.7)$$

Here,  $k_i$  is the effective stiffness of the wormhole in Plexus  $i$ , and  $n_i \in \mathbb{N}$  defines its mode number relative to the Planck scale. This implies that each force Plexus is built from wormholes of characteristic length  $\ell_i$ , inversely proportional to their oscillator frequency. Higher-frequency (shorter-length) wormholes dominate in high-energy forces like the strong interaction, while longer wormholes underlie gravity and electromagnetic interactions.

These discrete lengths form a natural lattice of allowable spacetime connections for each Plexus. Particle perimeters can only couple to wormholes with matching oscillator mode, introducing force-specific selection rules and quantized interaction distances. In this view, gauge symmetry arises not from continuous field degrees of freedom, but from discrete resonance compatibility between perimeter loops and wormhole oscillators.

## 1.8 Force Quantization and Resonance

Each force-specific Plexus emerges from perimeter-induced fluxes on particles that stimulate resonant wormhole creation. The oscillator model introduces a resonance condition for each virtual boson:

$$\omega_n = n\omega_0, \quad \text{only integer harmonics allowed} \quad (1.8)$$

Thus, force carriers (virtual bosons) must match allowed oscillator modes, introducing selection rules. Only harmonics resonant with the geometry of the particle's perimeter can be emitted or absorbed. These selection rules explain quantized boson emissions, aligning with QED's photon interactions and QCD's gluon exchanges.

## 1.9 Entanglement as Oscillator Synchronization

Entanglement in this framework is the phase-locked synchronization of oscillator states between spatially separated wormholes. Suppose two wormholes  $A$  and  $B$  form at spacelike-separated points, yet share a common oscillator phase:

$$\psi_{AB}(x, t) = \frac{1}{\sqrt{2}}(|0\rangle_A |1\rangle_B + |1\rangle_A |0\rangle_B) \quad (1.9)$$

This superposition reflects a correlated mode state across two oscillators. The nonlocality of entanglement emerges from the pre-existing synchronized wormhole modes in the underlying foam. Entanglement collapse is then a local decoherence of these shared oscillator states, not faster-than-light communication. Unlike QFT's field-based entanglement, this model ties nonlocality to pre-existing wormhole connections, offering a geometric basis.

## 1.10 Gravitational Implications

Gravitational curvature arises from systematic gradients in wormhole oscillator populations. The Ricci tensor becomes a statistical measure of energy stored across oscillators in the gravity-specific Plexus. By integrating wormhole oscillator density, we reproduce Einstein's Field Equations:

$$G_{\mu\nu} = 8\pi G \langle T_{\mu\nu} \rangle_{\text{osc}} \quad (1.10)$$

Here,  $\langle T_{\mu\nu} \rangle_{\text{osc}}$  is the stress-energy tensor averaged over oscillating wormhole populations. This predicts gravitational wave perturbations testable by LIGO or Einstein Telescope, extending prior predictions.

## 1.11 Conclusion

Assuming each wormhole acts as a quantum harmonic oscillator introduces a unified foundation for field quantization, stability, energy conservation, and entanglement. This assumption strengthens the Wormhole Plexus model by rooting its discrete structure in well-understood quantum principles. The framework naturally resolves ultraviolet divergences, preserves Lorentz invariance, and allows testable predictions through deviations in vacuum energy, entanglement behavior, and force resonance spectra. Future work will explore experimental signatures in GW detectors and CMB data, inviting collaboration to test this framework.

### 1.11.1 Loop Excitations: Semi-Stable, Self-Renewing Structures with Quantum Jitter

Beyond individual links, the foam supports *loops*—closed chains of wormholes that behave as semi-stable, self-renewing excitations. A loop  $\mathcal{L}$  is a minimal closed sequence of links in a given plexus  $\alpha$  with total arclength  $L_{\mathcal{L}}$  and curvature  $\kappa(s)$ . Loops are the microscopic carriers of sector “charges” (e.g. U(1) phase for EM, chirality for weak, flux for strong) and act as localized sources for the effective fields.

**Energetics and renewal.** We model a loop’s mesoscopic energy as

$$E_{\mathcal{L}}^{(\alpha)} = \sum_{i \in \mathcal{L}} \left( n_i + \frac{1}{2} \right) \hbar \omega_{\alpha}(L_i) + \tau_{\alpha} L_{\mathcal{L}} + \frac{\kappa_{\alpha}}{2} \int_{\mathcal{L}} \kappa(s)^2 ds, \quad (1.11)$$

with link oscillator levels  $n_i$ , a line tension  $\tau_{\alpha}$ , and a bending rigidity  $\kappa_{\alpha}$ . Loops are *self-renewing*: they constantly rewire via local reconnection moves at a Poisson rate  $\lambda_{\text{ren}}^{(\alpha)}$ , balancing breakup and reclosure. The lifetime distribution is exponential with mean  $\langle \tau_{\mathcal{L}} \rangle \simeq (\lambda_{\text{split}}^{(\alpha)} - \lambda_{\text{join}}^{(\alpha)})^{-1}$  in the steady state; semi-stability corresponds to a small positive net rate.

**Dwell time: persistence before reconfiguration.** A loop does not remain in a single configuration indefinitely. Instead, it persists for a finite *dwell time*  $\tau_d$  before reconfiguration, governed by foam fluctuations. Statistically, we model dwell times as exponentially distributed:

$$P(\tau_d) = \frac{1}{\bar{\tau}_{\alpha}} \exp\left(-\frac{\tau_d}{\bar{\tau}_{\alpha}}\right), \quad (1.12)$$

with mean  $\bar{\tau}_{\alpha}$  set by sector-specific parameters  $(\mu_{\alpha}, \omega_{\alpha}, \pi_{\alpha})$ . This is the natural form for Poisson-driven processes, consistent with the memoryless rewiring of the foam.

**Energy–time uncertainty from dwell time.** Finite dwell time induces an intrinsic spectral broadening:

$$\Delta E_{\alpha} \Delta \tau_d \sim \hbar, \quad (1.13)$$

so shorter-lived loops correspond to larger energy spreads (vacuum jitter, virtual exchanges), while long-lived loops stabilize into persistent excitations (fermions, stable bosons). Intermediate dwell times underlie resonances and metastable states.

**Path integral weighting with dwell times.** Histories in the foam are weighted not only by their action  $S[x(t)]$  but also by dwell-time factors:

$$\Psi(x) = \oint \exp\left(\frac{i}{\hbar} S[x(t)]\right) \prod_j P(\tau_{d,j}) \mathcal{D}x, \quad (1.14)$$

so the path integral becomes a statistical sum over dwell-time-weighted loop histories. This bridges microscopic loop persistence with macroscopic quantum amplitudes.

**Quantum jitter (zitterbewegung of loops).** At Planck scales, loop centroids undergo jitter from discrete reconnections. A coarse model is an Ornstein–Uhlenbeck process for the loop centroid  $X^\mu(\tau)$ :

$$dX^\mu = V^\mu d\tau - \gamma_\alpha X^\mu d\tau + \sqrt{2D_\alpha} dW^\mu, \quad \langle \Delta X^2 \rangle \sim \frac{D_\alpha}{\gamma_\alpha} (1 - e^{-2\gamma_\alpha \tau}), \quad (1.15)$$

with diffusion constant  $D_\alpha \sim c \ell_P$  and relaxation  $\gamma_\alpha \sim \omega_\alpha$ . In the UV ( $\tau \ll \gamma_\alpha^{-1}$ ),  $\langle \Delta X^2 \rangle \sim 2D_\alpha \tau$  (diffusive); in the IR it saturates at  $D_\alpha/\gamma_\alpha$ , giving a finite jitter amplitude.

**Topological labels and sector charges.** Each loop carries discrete labels:  $w \in \mathbb{Z}$  (winding/flux),  $\chi = \pm 1$  (chirality/handedness), and sector charge  $q_\alpha$ . These are conserved under local moves and define the *source content* of a loop.

**Loop currents as sources for effective fields.** Let the loop worldline (or worldsheet surrogate) generate a conserved current  $J_{(\alpha)}^\mu(x)$  and a stress tensor  $T_{(\alpha)}^{\mu\nu}(x)$ . Couplings in the effective theory are

$$S_{\text{src}} = \int d^4x \left[ T_{(\text{grav})}^{\mu\nu} h_{\mu\nu} + J_{(\text{EM})}^\mu A_\mu + \mathcal{J}_{(\text{weak})}^{a\mu} W_\mu^a + \mathcal{J}_{(\text{strong})}^{A\mu} \mathcal{A}_\mu^A + y_H |\Phi_H|^2 \rho_{\mathcal{L}} \right], \quad (1.16)$$

where  $h_{\mu\nu}$  is the metric perturbation,  $A_\mu$  the EM potential,  $W_\mu^a$  and  $\mathcal{A}_\mu^A$  stand for non-Abelian gauge fields after coarse-graining,  $y_H$  is a foam Yukawa-like coupling, and  $\rho_{\mathcal{L}}$  is the coarse loop density. Thus, loops are the microscopic *emitters and absorbers* of plexus fields. And more fundamentally they act as amplifiers: self-renewing structures that stabilize and magnify stochastic foam fluctuations into persistent, macroscopic forces.

**Why loops matter.** (i) They provide a concrete micro-origin for particle-like excitations and charges; (ii) their jitter explains universal short-scale noise floors; (iii) their renewal stabilizes long-lived excitations without postulating fundamental point particles. In the exterior of compact sources, loop-induced sources vanish or dilute, so the gravitational sector reduces to the GR vacuum, with all foam corrections confined to the saturated interior.

### 1.11.2 Gravity Plexus

**1. What is it?** Gravity is the universal attraction that shapes spacetime geometry. In the Foam–Plexus model, gravity arises from the **gravitational plexus**: a dense, nearly isotropic web of wormholes that resists unlimited packing. Unlike other plexuses, it has no charge sign and couples equally to all forms of energy. Its defining trait is **saturation**: there is a maximum wormhole density, which regularizes black-hole cores and prevents singularities.

**2. How it arises from the foam.** Each gravitational wormhole is treated as a harmonic oscillator with frequency

$$\omega_{\text{grav}}(L) = \omega_{g0} \sqrt{1 + \left( \frac{\ell_P}{L} \right)^p}, \quad (1.17)$$

stiffening in the ultraviolet as lengths approach the Planck scale  $\ell_P$ .

The gravitational sector’s free-energy density is

$$\mathcal{F}_{\text{grav}}[\rho_g] = \frac{K_g}{2} (\nabla \rho_g)^2 + \frac{a_g}{2} (\rho_g - \bar{\rho}_g)^2 + \frac{b_g}{4} (\rho_g - \bar{\rho}_g)^4 + \sigma_g \frac{\rho_g^2}{\rho_{\text{max}} - \rho_g}, \quad 0 < \rho_g < \rho_{\text{max}}. \quad (1.18)$$

Here:

- $K_g$  controls the stiffness of density gradients,
- $a_g, b_g$  set equilibrium fluctuations,
- $\sigma_g$  enforces saturation near  $\rho_{\text{max}}$ .

**3. Gives rise to General Relativity.** When we coarse-grain this functional and vary it with respect to an emergent metric  $g_{\mu\nu}$  built from invariants of  $\rho_g$ , the long-wavelength Euler–Lagrange equations reduce to the **Einstein–Hilbert action**:

$$S_{\text{EH}} = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R, \quad (1.19)$$

with Newton’s constant emerging as a susceptibility,

$$G^{-1} \sim K_g \chi_g(a_g, b_g, \rho_{\text{max}}, \dots). \quad (1.20)$$

Thus, outside compact sources the geometry reduces *exactly* to the GR vacuum solution (e.g., Schwarzschild/Kerr metrics). Inside, however, the saturation term prevents  $\rho_g$  from diverging, replacing singularities with a finite-density core.

**4. Signatures.** Because the exterior is pure GR, deviations show up only near strong-field regions:

- **Near-horizon micro-corrections:** subtle phase shifts in black-hole ringdown spectra.
- **Regularized cores:** potentially alter late-time collapse or gravitational wave echoes.
- **Universal coupling:** stochastic background strain floor from Planck-scale foam jitter.

### 1.11.3 Electromagnetic Plexus

**1. What is it?** Electromagnetism is the long-range interaction that governs charges, light, and radiation. In the Foam–Plexus model, it arises from the **electromagnetic plexus**: a network of wormhole loops that carry a U(1) phase. Unlike gravity, this plexus distinguishes between positive and negative charge, and its order parameter naturally supports oscillations that propagate as photons.

**2. How it arises from the foam.** Each electromagnetic wormhole is modeled as a harmonic oscillator with a milder length dependence:

$$\omega_{\text{EM}}(L) = \omega_{e0} \sqrt{1 + \alpha_e \left( \frac{\ell_P}{L} \right)}. \quad (1.21)$$

The microscopic links also carry a phase label  $\theta_i$ , minimally coupled through link variables  $A_{ij}$ .

At the coarse-grained level we introduce a complex order parameter

$$\Psi_{\text{EM}} = \sqrt{\rho_{w,\text{EM}}} e^{i\theta},$$

whose phase tracks the emergent vector potential.

The electromagnetic free-energy density is

$$\mathcal{F}_{\text{EM}}[\Psi, \mathbf{A}] = K_{\text{EM}} |(\nabla - iq_{\text{eff}} \mathbf{A})\Psi|^2 + m_{\text{EM}}^2 |\Psi|^2 + \lambda_{\text{EM}} |\Psi|^4. \quad (1.22)$$

**3. Gives rise to Maxwell’s equations.** Integrating out amplitude fluctuations at long wavelengths leaves a kinetic term for the gauge field:

$$\mathcal{L}_{\text{Maxwell}} = -\frac{1}{4\mu_0} F_{\mu\nu} F^{\mu\nu}, \quad (1.23)$$

with

$$\epsilon_0^{-1}, \mu_0^{-1} \sim K_{\text{EM}} \chi_{\text{EM}}(m_{\text{EM}}, \lambda_{\text{EM}}, q_{\text{eff}}).$$

Thus, the Maxwell equations emerge as the coarse-grained dynamics of the EM plexus. Photons appear as collective excitations of wormhole loops that oscillate coherently across the network.

**4. Signatures.** Because Maxwell’s equations are recovered at large scales, deviations are tiny but potentially observable:

- **Energy-dependent photon speed:** Planck-suppressed dispersion relations could produce time delays in gamma-ray bursts.
- **Fine-structure variation:** small redshift-dependent shifts in  $\alpha$  from foam fluctuations.
- **Extreme-field birefringence:** ultra-weak polarization effects in intense laser or magnetar environments.

### 1.11.4 Strong Plexus

**1. What is it?** The strong interaction binds quarks into protons, neutrons, and nuclei. In the Foam–Plexus model, it arises from the **strong plexus**: a dense clustering of wormholes that naturally form “bundles” or flux tubes. This plexus is distinguished by its self-reinforcing nature — once wormholes cluster, they pull in more connections, amplifying the effect.

**2. How it arises from the foam.** Strong-sector wormholes favor short lengths and tight orientations, captured by  $\pi_{\text{strong}}(L, \Omega)$  and  $\omega_{\text{strong}}(L)$  that penalize long links. At the effective level, this clustering is encoded as

$$\mathcal{F}_{\text{strong}}[\rho_s] = \frac{K_s}{2}(\nabla\rho_s)^2 + \frac{m_s^2}{2}\rho_s^2 + \frac{\lambda_s}{4}\rho_s^4 - \frac{g_s}{2}\rho_s(-\nabla^2 + \xi_s^{-2})^{-1}\rho_s, \quad (1.24)$$

where the nonlocal kernel with scale  $\xi_s$  favors tube-like bundles that resist separation.

**3. Gives rise to SU(3).** When coarse-grained, the clustering order parameter can be promoted from a scalar density  $\rho_s$  to an SU(3) matrix-valued field representing color charge. The gradient terms then yield the Yang–Mills kinetic action:

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu}, \quad F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c.$$

Thus the strong plexus recovers QCD confinement at large scales, with flux-tube physics built in from the foam.

### 4. Signatures.

- Natural explanation of confinement: quarks are never isolated because plexus wormholes self-bundle into tubes.
- String tension of hadrons linked to foam parameters  $g_s, \xi_s$ .
- Possible deviations in hadron spectra or jet fragmentation at very high energies if foam clustering slightly modifies QCD scaling.

### 1.11.5 Weak Plexus

**1. What is it?** The weak interaction is responsible for processes like beta decay and neutrino interactions. In the Foam–Plexus model, it arises from the **weak plexus**: a wormhole network with a built-in handedness. This plexus is unique because it breaks parity symmetry: it prefers left-handed over right-handed orientations.

**2. How it arises from the foam.** Weak wormholes are modeled as oscillators with orientation labels that distinguish chirality. The microscopic distribution  $\pi_{\text{weak}}(L, \Omega)$  is biased, favoring loops that twist with a particular handedness.

At the coarse level, the effective free energy is

$$\mathcal{F}_{\text{weak}}[\mathbf{n}_w, \rho_w] = \frac{K_1}{2}(\nabla\mathbf{n}_w)^2 + \frac{K_2}{2}(\mathbf{n}_w \cdot \nabla \times \mathbf{n}_w)^2 + \frac{K_3}{2}\|\mathbf{n}_w \times (\nabla \times \mathbf{n}_w)\|^2 + \gamma_w \mathbf{n}_w \cdot (\nabla \times \mathbf{n}_w) + V_w(\rho_w). \quad (1.25)$$

Here  $\mathbf{n}_w$  is a unit director encoding loop orientation, while the linear “cholesteric” term  $\gamma_w$  explicitly breaks parity.

**3. Gives rise to  $SU(2)_L$ .** Coarse-graining this sector and promoting orientations to matrices yields an  $SU(2)$  gauge field with left-handed coupling. Thus the weak plexus reproduces the  $SU(2)_L$  structure of the Standard Model. The parity-violating term explains why only left-handed fermions couple strongly to the weak force.

#### 4. Signatures.

- Subtle parity-odd correlations in scattering experiments.
- Possible micro-asymmetries seeded in the early universe.
- Foam-level deviations suppressed at accessible energies but could appear in precision electroweak tests.

### 1.11.6 Higgs Plexus

**1. What is it?** The Higgs field gives mass to particles. In the Foam-Plexus model, it arises from the **Higgs plexus**: wormhole loops that self-saturate, creating a stable background density. This plexus does not transmit a long-range force, but instead sets the mass scale for fermions and bosons.

**2. How it arises from the foam.** Higgs wormholes are modeled as softer oscillators that condense into a collective order parameter  $\Phi_H$ . The effective free energy is the familiar “Mexican-hat” form:

$$\mathcal{F}_H[\Phi_H] = K_H |\nabla \Phi_H|^2 - \mu_H^2 |\Phi_H|^2 + \lambda_H |\Phi_H|^4, \quad \langle |\Phi_H| \rangle = \frac{\mu_H}{\sqrt{\lambda_H}} = \frac{v}{\sqrt{2}}. \quad (1.26)$$

Here the vacuum expectation value  $v$  arises as the saturation density of Higgs-type wormhole loops.

**3. Gives rise to mass.** When the Higgs plexus condenses, its vacuum density couples to the other plexuses. Cross-terms such as

$$\mathcal{F}_{\text{cross}} \supset g_{gH} (\rho_{w,\text{grav}} - \bar{\rho}_g) |\Phi_H|^2 + g_{EH} |\Psi_{\text{EM}}|^2 |\Phi_H|^2 + \dots \quad (1.27)$$

communicate the Higgs vacuum into gravity, electromagnetism, and the weak sector. As a result, gauge bosons and fermionic loops acquire inertial mass.

#### 4. Signatures.

- Correlated variations of particle masses in regions of extreme gravity.
- Small horizon-scale deviations if the Higgs plexus density shifts near compact objects.
- Possible foam-induced corrections to Higgs couplings, testable at high-precision colliders.

### 1.11.7 Exterior Geometry Reduces to GR

Because  $V_{\text{grav}}(\rho_g)$  is regular away from saturation and gradients dominate in the IR, the stationary-phase equations outside compact sources reduce *exactly* to the GR vacuum equations. All foam corrections are confined to the UV/interior (core saturation, near-horizon microstructure). Newton’s constant is an *emergent susceptibility*

$$G^{-1} \sim K_g \chi_g(\mu_{\text{grav}}, \pi_{\text{grav}}, \omega_{\text{grav}}; a_g, b_g, \rho_{\text{max}}),$$

so the observed  $G$  is determined by micro-parameters rather than tuned post hoc.

### 1.11.8 Two-Scale Picture (what to remember)

- **Microscopic layer:** a single stochastic foam of wormholes, each treated as a harmonic oscillator with type-dependent frequency  $\omega_\alpha(L)$  and statistics  $\pi_\alpha$ .
- **Effective layer:** plexus order parameters  $\{\rho_\alpha, \Psi_{\text{EM}}, \mathbf{n}_w, \Phi_H\}$  with gradient moduli  $K_\alpha$  and potentials  $V_\alpha$  yield the known IR theories (GR, Maxwell/YM, Higgs). Inter-plexus terms enforce universality and SSB.

In short: spacetime is a multiplex foam. QFT and GR are its thermodynamic faces.

## 1.12 Deriving Classical Fields

In the Foam–Plexus framework, classical fields are not fundamental entities but the *statistical outcomes of wormhole density gradients*. What physicists usually write as smooth fields—gravitational, electric, or gauge—are simply the coarse-grained averages of countless stochastic alignments inside the quantum foam. Loops act as microscopic amplifiers, sourcing gradients in their parent plexuses, and the macroscopic consequence is the appearance of long-range fields.

### 1.12.1 Newtonian Gravity as Creation–Dwell–Absorption in the Gravitational Plexus

**Microscopic balance (conceptual).** In the gravitational plexus, the coarse wormhole density  $\rho_g(x)$  is the steady outcome of three stochastic processes: (i) *creation* of links catalyzed by matter loops, (ii) finite *dwell time* of created links before decay, and (iii) *absorption* of links back into the foam. At mesoscopic scales this is captured by

$$\frac{\partial \rho_g}{\partial t}(x) = R_{\text{create}}[\rho_M](x) - \frac{\rho_g(x) - \rho_{g0}}{\tau_{\text{dwell}}} + D_g \nabla^2 \rho_g(x), \quad (1.28)$$

where  $\rho_M$  is the coarse loop (mass) density,  $\rho_{g0}$  is the homogeneous background density in the absence of sources,  $\tau_{\text{dwell}}$  is the mean survival time of a link, and  $D_g$  is an effective diffusion arising from local rewiring moves. The creation functional embodies universality:

$$R_{\text{create}}[\rho_M](x) = \alpha_g \int d^3 x' K_\ell(|x - x'|) \rho_M(x'), \quad \int d^3 x K_\ell(|x|) = 1, \quad (1.29)$$

with  $\alpha_g$  a microscopic amplification coefficient and  $K_\ell$  a short-range kernel of width  $\ell = \mathcal{O}(\ell_P)$  that coarse-grains loop sources.

**Steady state and screened Poisson form.** In stationary conditions ( $\partial_t \rho_g = 0$ ) and defining the excess density  $\delta \rho_g \equiv \rho_g - \rho_{g0}$ , Eqs. (1.28)–(1.29) give

$$D_g \nabla^2 \delta \rho_g(x) - \frac{\delta \rho_g(x)}{\tau_{\text{dwell}}} = -\alpha_g \int d^3 x' K_\ell(|x - x'|) \rho_M(x'). \quad (1.30)$$

At radii  $r \gg \ell$  (and away from saturation), we may replace the convolution by  $\rho_M(x)$ :

$$\left( \nabla^2 - \lambda_g^2 \right) \delta \rho_g(x) = -S_g \rho_M(x), \quad \lambda_g^2 \equiv \frac{1}{D_g \tau_{\text{dwell}}}, \quad S_g \equiv \frac{\alpha_g}{D_g}. \quad (1.31)$$

Thus  $\delta \rho_g$  obeys a Helmholtz (screened Poisson) equation with screening length  $L_g \equiv \lambda_g^{-1} = \sqrt{D_g \tau_{\text{dwell}}}$ . In the weak-screening regime relevant to astrophysical scales ( $r \ll L_g$ ), this reduces to the Poisson form

$$\nabla^2 \delta \rho_g(x) = -S_g \rho_M(x) \quad (r \ll L_g). \quad (1.32)$$

**Point source:  $1/r$  density,  $1/r^2$  acceleration.** For a compact source  $\rho_M(x) = M \delta^{(3)}(x)$ , Eq. (1.32) gives

$$\delta \rho_g(r) = \frac{S_g M}{4\pi r} \quad (r \ll L_g), \quad \Rightarrow \quad \nabla \delta \rho_g(r) = -\frac{S_g M}{4\pi} \frac{\hat{r}}{r^2}. \quad (1.33)$$

The macroscopic gravitational acceleration is the susceptibility-weighted density gradient,

$$\vec{g}(r) = k_g \nabla \rho_g(r) = k_g \nabla \delta \rho_g(r) = -\frac{k_g S_g}{4\pi} \frac{M}{r^2} \hat{r}. \quad (1.34)$$

Matching Newton’s law  $g(r) = GM/r^2$  fixes the *emergent* Newton constant as a composite foam susceptibility

$$G = \frac{k_g S_g}{4\pi} = \frac{k_g}{4\pi} \frac{\alpha_g}{D_g} = \frac{k_g}{4\pi} \frac{\alpha_g}{L_g^2 / \tau_{\text{dwell}}} = \frac{k_g \alpha_g \tau_{\text{dwell}}}{4\pi L_g^2}, \quad (1.35)$$

exhibiting explicitly how  $G$  emerges from microscopic creation ( $\alpha_g$ ), dwell ( $\tau_{\text{dwell}}$ ), and transport ( $D_g$  or  $L_g$ ) parameters. This is a calibration-by-definition, not a post hoc tune.

**Gauss’s law and the inverse-square signature.** Integrating Eq. (1.32) over a ball of radius  $r$  and using the divergence theorem,

$$\int_{S_r} \nabla \delta \rho_g \cdot d\mathbf{S} = -S_g M_{\text{enc}}(r). \quad (1.36)$$

For a point mass,  $M_{\text{enc}}(r) = M$ , so the outward flux of  $\nabla \delta \rho_g$  through the sphere is constant with  $r$ . Since  $S_r = 4\pi r^2$  grows as the surface area, the radial field must decay as  $1/r^2$ . Multiplying by  $k_g$  (Eq. (1.34)) yields Newton’s inverse-square law.

**Remarks.** (i) The screening length  $L_g = \sqrt{D_g \tau_{\text{dwell}}}$  sets how far creation persists before absorption cancels it; the Newtonian regime holds for  $r \ll L_g$ . (ii) Near compact interiors, additional saturation terms (introduced in the gravitational free energy) regulate  $\rho_g \rightarrow \rho_{\text{max}}$  without altering the exterior  $1/r^2$  field. (iii) Equation (1.35) makes transparent which micro-parameters control  $G$  and, conversely, what precision tests of gravity constrain in the foam.

### 1.12.2 Relay–Cascade Transport and Causal Propagation

We model loop–foam interactions as a *relay* (absorption  $\rightarrow$  re-emission) that, on coarse scales, appears as a weakly biased, persistent random walk of gravitational links. Let  $\rho_g(\mathbf{x}, t)$  denote the coarse density of outward-carrying gravitational links, and  $\mathbf{J}_g$  their flux. Three microscopic ingredients fix the transport:

- **Creation (bias):** loop sources create outward-oriented links at rate density  $\Gamma(\mathbf{x})$  (total  $\propto M$ ).
- **Dwell:** links persist for a mean dwell time  $\tau$  before decaying back into the foam.
- **Relay (re-emission):** each decay triggers a new outward link with probability  $p \in (0, 1)$  and a small outward bias, producing a drift speed  $v_b$ ; unbiased recoils yield diffusion with coefficient  $D$ .

A standard coarse-graining of a persistent random walk with finite lifetime (the “telegraph” limit) gives the *causal* transport system

$$\partial_t \rho_g + \nabla \cdot \mathbf{J}_g = \Gamma - \frac{1-p}{\tau} \rho_g, \quad (1.37)$$

$$\tau \partial_t \mathbf{J}_g + \mathbf{J}_g = -D \nabla \rho_g + v_b \rho_g \hat{\mathbf{r}}. \quad (1.38)$$

Eliminating  $\mathbf{J}_g$  yields a *telegrapher equation* for  $\rho_g$ :

$$\tau \partial_t^2 \rho_g + \partial_t \rho_g = D \nabla^2 \rho_g - \frac{1-p}{\tau} \rho_g + \partial_t \Gamma. \quad (1.39)$$

Equation (1.39) propagates disturbances at finite *foam speed*

$$c_f = \sqrt{D/\tau}, \quad (1.40)$$

augmented by the small drift  $v_b$  (so signals move no faster than  $c_f + v_b$ ). Thus the gravitational plexus responds causally to source changes.

**Steady exterior field and the  $1/r$  profile.** Outside the compact source ( $\Gamma = 0$ ) and at late times ( $\partial_t \rho_g = 0$ ), Eq. (1.37) gives  $\nabla \cdot \mathbf{J}_g = -\frac{1-p}{\tau} \rho_g$ . For weak loss  $(1-p) \rightarrow 0$  the flux becomes *divergence-free*, so in spherical symmetry  $4\pi r^2 J_r(r) = \Phi = \text{const.}$  If drift is negligible compared to diffusion on these scales ( $v_b \ll D/r$ ), then  $J_r \approx -D \partial_r \rho_g$  and

$$-D \frac{d\rho_g}{dr} = \frac{\Phi}{4\pi r^2} \Rightarrow \rho_g(r) = \rho_\infty + \frac{A}{r}, \quad A = \frac{\Phi}{4\pi D}. \quad (1.41)$$

Therefore

$$\nabla \rho_g(r) = -\frac{A}{r^2} \hat{\mathbf{r}}, \quad \vec{g}(r) = k_g \nabla \rho_g(r) = -\frac{k_g A}{r^2} \hat{\mathbf{r}}, \quad (1.42)$$

so the inverse-square law appears as the *surface-area sharing* of a conserved outward flux across spheres of area  $4\pi r^2$ .

**Emergent  $G$  and micro–macro map.** Matching Eq. (1.42) to Newton’s law  $|\vec{g}| = GM/r^2$  fixes

$$G = k_g \frac{\Phi}{4\pi D M} \equiv \mathcal{G}(D, \tau, p, v_b; \text{loop yield}), \quad (1.43)$$

i.e. Newton’s constant is an *emergent susceptibility* determined by the transport parameters  $(D, \tau, p, v_b)$  and the loop-to-flux yield  $\Phi/M$ . Microscopic estimates give  $D \sim \ell^2/(3\tau)$  (with step length  $\ell \sim \text{few } \ell_P$ ), so  $c_f = \sqrt{D/\tau} \sim \ell/(\sqrt{3}\tau)$ , linking the macroscopic *response speed* of gravity to foam dwell-time and step size. Rare, ultra-long links (nonlocal events) can be included as small corrections to  $\Phi$  without altering the  $1/r$  profile.

**Summary.** (i) *Relay* (decay  $\rightarrow$  re-emission) plus weak outward bias builds a smooth, outward flux. (ii) *Cascade* (quasi-conserved flux) across growing spherical shells yields  $\rho_g \propto 1/r$  and hence  $|\vec{g}| \propto 1/r^2$ . (iii) The *telegraph* form guarantees finite-speed response  $c_f$  set by foam microphysics, while the steady exterior reduces to the Newtonian limit with  $G$  emergent from  $(D, \tau, p, v_b)$  and the loop yield.

### 1.12.3 Electromagnetism from Foam Alignments: Classical Limit

**What is it?** Electromagnetism arises from the *electromagnetic plexus*—wormholes carrying a  $U(1)$  phase label. Charged loops (sources) bias the foam so that EM links preferentially align *outward* for  $q > 0$  and *inward* for  $q < 0$ . The macroscopic electric field is the coarse gradient of this biased link density.

**Mesoscopic kinetics (creation–transport–relaxation).** Let  $\rho_e(\mathbf{x}, t)$  be the coarse EM-plexus link density. We model its dynamics by a linear reaction–transport equation with a  $U(1)$ -biased source:

$$\partial_t \rho_e + \nabla \cdot \mathbf{J}_e = \mathcal{R}_e S_e(\mathbf{x}, t) - \frac{\rho_e - \bar{\rho}_e}{\tau_e}, \quad \mathbf{J}_e = -D_e \nabla \rho_e, \quad (1.44)$$

where  $\mathcal{R}_e$  is the creation (amplification) rate,  $\tau_e$  the mean dwell time,  $D_e$  an effective diffusivity, and  $\bar{\rho}_e$  the homogeneous background. For a static point charge  $q$  at the origin, the source is taken as

$$S_e(\mathbf{x}) = \sigma_e q \delta^3(\mathbf{x}), \quad (1.45)$$

with  $\sigma_e$  a (positive) microscopic bias factor fixed by the foam statistics of charged loops.

**Steady state (Coulomb sector).** In the quasistatic regime ( $\partial_t \rho_e \approx 0$ ) Eqs. (1.44)–(1.45) give

$$-D_e \nabla^2 \rho_e = \mathcal{R}_e \sigma_e q \delta^3(\mathbf{x}) - \frac{\rho_e - \bar{\rho}_e}{\tau_e}. \quad (1.46)$$

At distances  $r \gg \lambda_e \equiv \sqrt{D_e \tau_e}$  the relaxation term is negligible compared to gradients, so we obtain the Poisson limit

$$-D_e \nabla^2 \rho_e = \mathcal{R}_e \sigma_e q \delta^3(\mathbf{x}). \quad (1.47)$$

The spherically symmetric solution (with  $\rho_e \rightarrow \bar{\rho}_e$  as  $r \rightarrow \infty$ ) is

$$\rho_e(r) = \bar{\rho}_e + \frac{\mathcal{R}_e \sigma_e q}{4\pi D_e} \frac{1}{r}. \quad (1.48)$$

We identify the macroscopic electric field with the density gradient,

$$\mathbf{E}(\mathbf{x}) \equiv k_e \nabla \rho_e(\mathbf{x}), \quad (1.49)$$

so that

$$\mathbf{E}(\mathbf{r}) = k_e \frac{\mathcal{R}_e \sigma_e q}{4\pi D_e} \frac{1}{r^2} \hat{\mathbf{r}}. \quad (1.50)$$

Matching to Coulomb’s law fixes the (emergent) susceptibility combination:

$$\boxed{\frac{k_e \mathcal{R}_e \sigma_e}{D_e} = \frac{1}{\epsilon_0}} \quad \implies \quad \mathbf{E}(\mathbf{r}) = \frac{q}{4\pi \epsilon_0 r^2} \hat{\mathbf{r}}. \quad (1.51)$$

**Field equations and gauge structure (time dependence).** Define the potential via the coarse U(1) phase  $\theta(x)$ :

$$A_\mu \equiv \frac{1}{q_{\text{eff}}} \partial_\mu \theta, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \quad (1.52)$$

which is invariant under  $\theta \rightarrow \theta + \Lambda$  (thus  $A_\mu \rightarrow A_\mu + \partial_\mu \Lambda / q_{\text{eff}}$ ). Linear response of the foam gives the constitutive relations

$$\mathbf{D} = \epsilon_0 \mathbf{E}, \quad \mathbf{B} = \mu_0 \mathbf{H}, \quad \epsilon_0^{-1} \equiv \frac{k_e \mathcal{R}_e \sigma_e}{D_e}, \quad \mu_0 \equiv \frac{\chi_B}{K_B}, \quad (1.53)$$

where  $\chi_B / K_B$  is the magnetic susceptibility-to-stiffness ratio obtained by coarse-graining the phase-rigidity sector. Charge and current densities arise from loop sources  $(\rho_q, \mathbf{J}_q)$ , which obey  $\partial_t \rho_q + \nabla \cdot \mathbf{J}_q = 0$ . Then the macroscopic equations are the Maxwell system:

$$\nabla \cdot \mathbf{D} = \rho_q, \quad \nabla \times \mathbf{H} = \mathbf{J}_q + \partial_t \mathbf{D}, \quad \nabla \cdot \mathbf{B} = 0, \quad \nabla \times \mathbf{E} = -\partial_t \mathbf{B}. \quad (1.54)$$

Combining (1.53)–(1.54) yields the wave equation

$$(\nabla^2 - \frac{1}{c^2} \partial_t^2) \mathbf{E} = 0, \quad c^{-2} = \epsilon_0 \mu_0, \quad (1.55)$$

so the foam's susceptibilities set the emergent light speed.

**Dictionary (foam  $\rightarrow$  classical).** In summary,

$$\begin{aligned} \mathbf{E} &= k_e \nabla \rho_e, \\ \epsilon_0^{-1} &= \frac{k_e \mathcal{R}_e \sigma_e}{D_e}, \\ c^{-2} &= \epsilon_0 \mu_0, \\ \text{Coulomb law : } \mathbf{E} &= \frac{q}{4\pi\epsilon_0 r^2} \hat{\mathbf{r}}, \\ \text{Maxwell eqs. : } &\text{Eqs. (1.54) with } \mathbf{D} = \epsilon_0 \mathbf{E}, \mathbf{B} = \mu_0 \mathbf{H}. \end{aligned}$$

(1.56)

Thus, Coulomb's inverse-square law is the far-field ( $r \gg \lambda_e$ ) limit of the foam's biased link density, while full Maxwell dynamics (including gauge invariance and the vacuum light speed  $c$ ) emerge from the phase-rigid, U(1)-symmetric coarse-grained sector of the EM plexus.

#### 1.12.4 From Density to Geometry: Metric and Curvature

**What is it?** Gravity at the continuum level is nothing more than the *geometry induced by averaged wormhole density*. When coarse-grained, the gravitational plexus density field  $\rho_g(x)$  encodes effective distances and causal structure. In particular, gradients and second derivatives of  $\rho_g$  map naturally to curvature.

**From density to metric.** We introduce an emergent metric tensor  $g_{\mu\nu}(x)$  defined as the coarse response of light-cone distances to wormhole density fluctuations:

$$g_{\mu\nu}(x) \equiv \eta_{\mu\nu} + \chi_g \partial_\mu \partial_\nu \rho_g(x), \quad (1.57)$$

where  $\eta_{\mu\nu}$  is the Minkowski background and  $\chi_g$  a susceptibility constant derived from the foam. Thus, deviations in  $\rho_g$  curve the effective manifold.

**Connectivity tensor as orientation measure.** Beyond scalar density, the foam supports a tensorial measure of connectivity:

$$C_{\mu\nu}(x) \equiv \langle d_w^\mu d_w^\nu \rangle, \quad (1.58)$$

where  $d_w^\mu$  are the local orientation vectors of wormhole links.  $C_{\mu\nu}$  captures the anisotropy and directional bias of the plexus. In isotropic equilibrium,  $C_{\mu\nu} \propto \eta_{\mu\nu}$ ; out of equilibrium, its eigenmodes define preferred directions and curvature sources.

**Foam Laplacian.** Standard quantum mechanics relies on the continuum Laplacian  $\nabla^2$ . In the Foam–Plexus model, discreteness replaces this with the *foam Laplacian*:

$$\Delta_C \psi(x) = \sum_{\langle i,j \rangle} C_{ij} (\psi_j - \psi_i), \quad (1.59)$$

where  $C_{ij}$  are the connectivity weights between sites  $i$  and  $j$ . In the dense limit,  $\Delta_C \rightarrow \nabla^2$ , recovering continuum physics. At finite connectivity, small deviations arise, offering a natural source of Planck-scale corrections to wave propagation and field dynamics.

**From metric to curvature.** Evaluating the Christoffel symbols from (1.57) and inserting into the Ricci tensor yields

$$R_{\mu\nu}(x) \sim \partial_\mu \partial_\nu \rho_g(x) + \cdots, \quad (1.60)$$

where the ellipsis denotes higher-order gradient corrections suppressed at long wavelengths. The Einstein tensor then follows as

$$G_{\mu\nu}(x) \propto \langle \rho_g(x) \rangle, \quad (1.61)$$

with proportionality fixed by foam susceptibilities, thereby reproducing Einstein’s equations in the macroscopic (infrared) limit.

**Why it matters.** Distances, causal structure, curvature, and even the Laplacian operator are *not primitive*. They are statistical summaries of connectivity in the wormhole foam. GR emerges as the continuum limit of  $\rho_g$  fluctuations, while the foam Laplacian  $\Delta_C$  provides a bridge from discrete wormhole dynamics to continuum field equations. This gives a statistical–mechanical origin for the metric and field operators, rather than assuming them as background structure.

### 1.12.5 Predictions from the Foam

**What is it?** The Foam–Plexus picture is falsifiable: it predicts small, structured deviations from a smooth manifold, all tied to quantized connectivity.

**Concrete predictions.**

- **Metric fluctuations:** Every distance measurement carries an irreducible uncertainty

$$\Delta x \sim \ell_P \equiv \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-35} \text{ m}.$$

This is a jitter floor, reflecting quantum foam discreteness.

- **Curvature from energy:** Local energy density biases wormhole alignments, so that

$$G_{\mu\nu} \sim \langle \rho_g \rangle,$$

reducing to Einstein’s equations at large scales but predicting small near-horizon corrections.

- **Cosmology:** Topological shifts in wormhole connectivity drive macroscopic phenomena: inflation as synchronized plexus realignment, dark energy as a statistical drift in residual connectivity, and horizon-scale correlations as relic imprints of stochastic foam bias.

**Why it matters.** In short: classical fields and geometry are not fundamental. They are *statistical gradients* of wormhole density, magnified by loop excitations, stabilized by self-renewal, and perceived by us as the Newtonian, Maxwellian, and Einsteinian laws of physics.

## 1.13 Statistical Origin of Lorentz Invariance

### 1.13.1 The Problem of Discreteness

Discrete spacetime models traditionally violate Lorentz invariance by introducing a preferred frame. The Foam–Plexus avoids this by modeling spacetime not as a grid but as a fluctuating ensemble of wormholes. Lorentz symmetry emerges as a statistical property.

### 1.13.2 Interaction Hamiltonian for Wormholes

The energy of the wormhole network is given by:

$$H[L_w] = \sum_i \left( \frac{\hbar c}{L_{w,i}} + \lambda \sum_{j \neq i} \cos \theta_{ij} \right), \quad (1.62)$$

where  $\cos \theta_{ij}$  encodes the alignment between wormhole  $i$  and  $j$ , and  $\lambda \sim \hbar c / \ell_P$  is an interaction strength. This resembles a spin-glass model, where the average isotropy restores symmetry.

### 1.13.3 On the Existence of an Action Principle in the Foam

A natural question arises once a Hamiltonian form has been written: does the quantum foam admit a fundamental *action principle*, or is action only meaningful after coarse-graining?

At the microscopic level, the foam is not a smooth manifold. Distances exist only along wormhole links, which are created and annihilated stochastically. Local transitions are governed by probabilistic weights of the form

$$P[\text{history}] \propto e^{-\beta H_{\text{foam}}},$$

where  $H_{\text{foam}}$  encodes link energies and interaction biases. This ensemble has no global, differentiable Lagrangian density, and thus no conventional action integral  $S = \int d^4x \mathcal{L}$ . In short: the raw foam has *no fundamental action principle*.

However, when one coarse-grains over many links, orientations, and loop excitations, the partition function reorganizes into a path integral of the familiar form

$$Z_{\text{eff}} = \int \mathcal{D}\Phi_\alpha e^{iS_{\text{eff}}[\{\Phi_\alpha\}]/\hbar},$$

with plexus order parameters  $\phi_\alpha$  defined as follows:

- **Gravity plexus**  $\rightarrow \rho_g(x)$ , the coarse wormhole density.
- **Electromagnetic plexus**  $\rightarrow \Psi_{\text{EM}}(x)$ , the complex order parameter carrying a U(1) phase.
- **Weak plexus**  $\rightarrow \mathbf{n}_w(x)$ , the chirality (handedness) director.
- **Higgs plexus**  $\rightarrow \Phi_H(x)$ , the condensate amplitude.

The effective action  $S_{\text{eff}}$  arises as the logarithm of the partition function, and its stationary-phase variation produces the continuum Euler–Lagrange equations.

Thus, the action principle is *emergent*: it does not belong to the stochastic foam itself, but appears once microscopic randomness is smoothed into effective fields. Einstein–Hilbert, Maxwell, and Yang–Mills actions are therefore understood not as fundamental laws, but as thermodynamic summaries of Planck-scale network dynamics.

This statistical reorganization is also what restores Lorentz symmetry: although no microscopic action exists, the emergent  $S_{\text{eff}}$  inherits isotropy from the underlying ensemble, ensuring that Lorentz invariance is preserved at macroscopic scales.

### 1.13.4 Statistical Distribution and Lorentz Recovery

The wormhole ensemble obeys a Boltzmann distribution:

$$P[L_w] = \frac{1}{Z} e^{-H[L_w]/kT}, \quad (1.63)$$

which ensures that any local anisotropy is smoothed out on average. Observables are Lorentz invariant because fluctuations occur randomly and densely over all directions.

### 1.13.5 Modified Dispersion and Experimental Signatures

At very high energies, wormhole relay–dwell statistics can in principle produce small deviations from the standard relativistic dispersion relation:

$$E^2 = p^2 c^2 + m^2 c^4 + \delta E^2, \quad \delta E^2 \sim \left( \frac{E}{E_{\text{Planck}}} \right)^n E^2, \quad (1.64)$$

with  $n = 1, 2$  depending on the scaling of the stochastic bias. Unlike many quantum–gravity scenarios, however, the Foam–Plexus model does not predict a one-sided delay. Relay and dwell processes can make individual quanta propagate slightly *faster* or *slower* than  $c$ , so over cosmological distances these deviations tend to cancel statistically.

**Observable consequence.** The net effect is therefore not a systematic energy-dependent delay, but a tiny stochastic broadening of arrival times, accumulating as a variance  $\Delta t \sim \sqrt{N} \tau_{\text{foam}}$  after  $N$  relay events of mean duration  $\tau_{\text{foam}}$ . Because source emission processes (e.g. GRB engines, FRB plasma dispersion) already produce natural pulse widths far larger than the foam-induced broadening, the stochastic signal is effectively swamped.

**Conclusion.** Although the model allows for Planck-suppressed dispersion, the predicted observational effect is a subdominant timing jitter, not a clean spectral lag. Thus, no realistically recognizable signal is expected in current astrophysical observations, even though the theoretical possibility remains. Astrophysical timing data therefore set only upper bounds on foam parameters, without offering a direct detection channel.

## 1.14 Emergent Gauge Fields from Wormhole Connectivity

In the Foam–Plexus model, gauge interactions are not postulated as fundamental symmetries but emerge from subnetworks of wormhole connections. Each plexus is a statistical sub-ensemble of links, and its connectivity encodes a corresponding gauge symmetry:

- **Electromagnetic plexus (U(1)):** phase-labeled wormholes whose link orientations encode a U(1) phase.
- **Weak plexus (SU(2)<sub>L</sub>):** chiral wormholes that carry a built-in handedness, breaking parity and naturally producing an SU(2)<sub>L</sub> structure.
- **Strong plexus (SU(3)):** bundles of color-labeled wormholes that cluster autocatalytically into tube-like structures, mapping onto SU(3) color interactions.

**Autocatalysis and feedback.** Unlike smooth background fields, plexuses grow via local feedback: once a density fluctuation in a plexus forms, it catalyzes the creation of more links of the same type. This exponential reinforcement—an *autocatalytic feedback*—is the microscopic origin of gauge-field self-interactions. In QCD, for instance, the self-bundling of color wormholes explains why flux tubes form and quarks are confined.

**Running couplings from oscillator activation.** Each wormhole link behaves as a harmonic oscillator with characteristic frequency  $\omega_\alpha(L)$ . At higher probe energies  $E$ , more oscillator modes are activated, increasing the effective coupling strength. This produces the familiar phenomenon of *running couplings*:

$$g_\alpha(E) \sim g_{\alpha,0} f_\alpha(E/E_{\text{Planck}}),$$

with the Planck scale acting as a natural cutoff that prevents divergences. Thus, asymptotic freedom in QCD and logarithmic running in QED are seen as statistical consequences of oscillator activation.

**Topology as the root of symmetry.** In this picture, gauge symmetries are not arbitrary group axioms but statistical invariances of wormhole plexus topologies. The U(1), SU(2), and SU(3) structures reflect phase labels, handedness, and color bundling respectively. Their field strengths emerge from coarse-graining connectivity, as in the tensor formalism:

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu + [A^\mu, A^\nu], \quad (1.65)$$

where the commutator arises precisely from autocatalytic link reinforcement.

**Predictions.** The Foam–Plexus model agrees with standard gauge theory in the infrared, but predicts small deviations:

- Modified running of couplings near the Planck scale with a hard cutoff rather than a Landau pole.
- Tiny departures from exact gauge symmetry in extreme conditions (near-horizon, early universe).
- Possible non-perturbative signatures from wormhole autocatalysis, such as subtle shifts in hadron spectra or rare scattering asymmetries.

# 2 The Coarse-Graining Chain: From Wormhole Oscillators to Continuum Fields and Spacetime

## 2.1 Overview

In the Foam-Plexus model, the fundamental degrees of freedom are Planck-scale wormholes whose lengths and orientations fluctuate as quantum harmonic oscillators. Their collective statistics determine the coarse-grained order parameters that define emergent spacetime geometry. This chapter presents the explicit chain:

Microscopic wormholes  $\rightarrow Z[\beta, \mu_\alpha] \rightarrow$  Coarse fields  $(n_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}} \rightarrow$  Einstein and gauge actions.

The goal is to show exactly how classical spacetime arises from the statistical mechanics of the quantum foam.

## 2.2 Microscopic Wormhole Oscillators

Each wormhole is labeled by its plexus type  $\alpha \in \{g, \text{EM}, w, s, H\}$  (gravity, electromagnetic, weak, strong, Higgs). Its microstate is described by:

- Length  $L_i \geq \ell_P$
- Orientation  $\hat{d}_i^\mu$  (unit 4-vector)
- Oscillator excitation number  $n_i = 0, 1, 2, \dots$

The single-wormhole Hamiltonian is modeled as a quantum harmonic oscillator:

$$H_i = \hbar\omega_\alpha(L_i) \left( n_i + \frac{1}{2} \right) + V_\alpha(\hat{d}_i) + H_{\text{cross}}. \quad (2.1)$$

Ultraviolet stiffening is incorporated through the  $L$ -dependence of the frequency:

$$\omega_\alpha(L) = \omega_{0,\alpha} \sqrt{1 + \left( \frac{\ell_P}{L} \right)^p}, \quad p \geq 2. \quad (2.2)$$

The orientation potential  $V_\alpha(\hat{d}_i)$  encodes plexus-specific alignment tendencies; for example, gravity plexus wormholes tend to align radially in the presence of mass-energy, while EM plexus wormholes align with phase gradients.

The cross-term  $H_{\text{cross}}$  accounts for interactions between neighboring wormholes, typically of the form

$$H_{\text{cross}} = - \sum_{i < j} J_{ij}^{(\alpha)} \mathcal{C}(\hat{d}_i, \hat{d}_j), \quad (2.3)$$

where  $\mathcal{C}$  measures orientation correlation.

## 2.3 Partition Function

The statistical ensemble is described by a grand-canonical partition function:

$$\mathcal{Z}[\beta, \{\mu_\alpha\}] = \sum_{\{N_\alpha\}} \prod_{\alpha} \frac{z_\alpha^{N_\alpha}}{N_\alpha!} \prod_{i=1}^{N_\alpha} \int dL_i d\Omega_i \pi_\alpha(L_i, \Omega_i) \frac{e^{-\beta \hbar \omega_\alpha(L_i)/2}}{1 - e^{-\beta \hbar \omega_\alpha(L_i)}} \langle e^{-\beta H_{\text{cross}}} \rangle. \quad (2.4)$$

Here:

- $z_\alpha = e^{\beta\mu_\alpha}$  is the fugacity for plexus type  $\alpha$ .
- $\pi_\alpha(L, \Omega)$  is the microscopic measure (stiffness, allowed angles).
- The factor

$$\frac{e^{-\beta\hbar\omega_\alpha/2}}{1 - e^{-\beta\hbar\omega_\alpha}}$$

is the standard HO partition function for a single wormhole.

- The angular integration  $d\Omega_i$  runs over all orientations  $\hat{d}_i$ .

All thermodynamic quantities follow from  $\mathcal{Z}$ :

$$\langle E \rangle = -\frac{\partial \ln \mathcal{Z}}{\partial \beta}, \quad \langle N_\alpha \rangle = \frac{\partial \ln \mathcal{Z}}{\partial (\beta\mu_\alpha)}.$$

## 2.4 Coarse-Grained Order Parameters

We now define coarse-grained fields over a volume  $V_c \gg \ell_P^3$ .

### 2.4.1 Density

The plexus-specific density is

$$\rho_\alpha(x) = \frac{1}{V_c} \sum_{i \in V_c} \delta_\alpha(i). \quad (2.5)$$

For gravity,  $\rho_g$  encodes wormhole clustering which will appear as curvature gradients.

### 2.4.2 Orientation / Alignment Fields

The alignment field for plexus  $\alpha$  is

$$A_\alpha^\mu(x) = \frac{1}{N_{\alpha,c}} \sum_{i \in V_c, \text{ plexus}=\alpha} \hat{d}_i^\mu. \quad (2.6)$$

In the Gravity-Plexus, gradients of  $A_g^\mu$  become components of Ricci curvature.

### 2.4.3 Complex Order Parameters

Some plexuses admit natural complex fields:

$$\Psi_{\text{EM}}(x) = \sqrt{\rho_{\text{EM}}(x)} e^{i\theta(x)}, \quad \Phi_H(x) = \sqrt{\rho_H(x)} e^{i\varphi(x)},$$

analogous to:

- $\theta(x)$ : EM phase  $\rightarrow$  gauge potential
- $\varphi(x)$ : Higgs phase  $\rightarrow$  mass generation

Weak plexus alignment is similarly expressed via a vector field

$$\mathbf{n}_w(x) = \frac{1}{N_w} \sum_{i \in V_c} \hat{d}_i^{(w)}.$$

These examples illustrate that each plexus yields its own coarse order parameter, but the procedure is uniform.

## 2.5 Effective Free Energy: Landau–Ginzburg Form

Integrating out the rapid microscopic fluctuations produces an effective action of Landau–Ginzburg form:

$$\mathcal{Z}_{\text{eff}} = \int \mathcal{D}\Phi_\alpha \exp \left[ -\beta \int d^4x \left( \sum_\alpha \mathcal{F}_\alpha[\Phi_\alpha] + \mathcal{F}_{\text{cross}}[\Phi_\alpha] \right) \right], \quad (2.7)$$

with

$$\mathcal{F}_\alpha[\Phi_\alpha] = \frac{K_\alpha}{2} (\nabla \Phi_\alpha)^2 + V_\alpha(\Phi_\alpha), \quad (2.8)$$

where:

- $K_\alpha$  is the stiffness determined by susceptibilities of the microscopic ensemble.
- $V_\alpha$  is the coarse potential obtained from the saddle–point evaluation of the local partition function.
- $\mathcal{F}_{\text{cross}}$  encodes inter–plexus interactions.

Equation (2.8) is universal: it applies to gravity, electromagnetism, weak, strong, and Higgs plexuses.

## 2.6 Gravity as a Worked Example

For the Gravity–Plexus, the relevant fields are:

$$n(x) \equiv \rho_g(x), \quad A^\mu(x) \equiv A_g^\mu(x).$$

A minimal effective Hamiltonian is

$$\mathcal{H}_{\text{eff}}[n, A^\mu] = \int d^4x \sqrt{-g} \left[ \alpha_1 n + \alpha_2 (\nabla_\mu n)^2 + \beta_1 A_\mu A^\mu + \beta_2 (\nabla_\mu A_\nu)(\nabla^\mu A^\nu) + \cdots \right]. \quad (2.9)$$

The metric  $g_{\mu\nu}$  is an order parameter encoding the statistical geometry of the wormhole ensemble. Varying the effective action

$$S_{\text{eff}}[g, n, A^\mu] = \int d^4x \sqrt{-g} \mathcal{H}_{\text{eff}}$$

with respect to  $g_{\mu\nu}$  yields:

$$G_{\mu\nu}[g] = T_{\mu\nu}^{(\text{foam})}, \quad (2.10)$$

where  $T_{\mu\nu}^{(\text{foam})}$  is constructed from  $n$  and  $A^\mu$ .

In the long–wavelength limit, we recover the Einstein–Hilbert action:

$$S_{\text{eff}} = \frac{1}{16\pi G_{\text{eff}}} \int d^4x \sqrt{-g} R + S_{\text{corr}}. \quad (2.11)$$

## 2.7 Summary of the Logical Chain

- (1) Planck-scale wormholes: HO modes, orientations, lengths  
↓
- (2) Grand canonical partition function  $\mathcal{Z}[\beta, \mu_\alpha]$   
↓
- (3) Coarse fields:  $\rho_\alpha, A_\alpha^\mu, \Psi_{\text{EM}}, \Phi_H$   
↓
- (4) Landau-Ginzburg free energy  $\mathcal{F}_\alpha = \frac{K_\alpha}{2}(\nabla\Phi_\alpha)^2 + V_\alpha(\Phi_\alpha)$   
↓
- (5) Variational principle  $\delta S_{\text{eff}}/\delta\Phi_\alpha = 0$   
↓
- (6) Emergent continuum fields: GR (gravity plexus),  
Maxwell (EM), Yang-Mills (weak/strong), Higgs potential

# 3 Emergent Physical Constants from Quantum Foam and Plexus Dynamics

## 3.1 abstract

In standard physics, fundamental constants such as the fine-structure constant ( $\alpha$ ), the gravitational constant ( $G$ ), and particle masses ( $m_e, m_p, m_H$ ) are treated as input parameters with no deeper explanation. This work proposes that these constants emerge naturally as statistical attractors in the evolving structure of quantum foam, specifically within the self-organizing interactions of the Gravity-Plexus, EM-Plexus, Strong Plexus, Weak Plexus, and Higgs-Plexus. We demonstrate that these constants could arise as equilibrium points in a self-consistent system of fluctuating spacetime, drawing parallels to thermodynamic systems and stable molecular structures. This perspective offers new testable predictions regarding possible deviations in physical constants under extreme conditions.

## 3.2 Introduction: Why Do Physical Constants Have Their Values?

The Standard Model of particle physics and General Relativity describe fundamental interactions using a set of measured constants:

- The fine-structure constant:  $\alpha \approx 1/137$
- The gravitational constant:  $G \approx 6.674 \times 10^{-11} \text{m}^3 \text{kg}^{-1} \text{s}^{-2}$
- The cosmological constant:  $\Lambda \approx 10^{-9} \text{J/m}^3$

Currently, these values are empirical inputs, with no deeper theoretical justification.

The Foam-Plexus model provides a novel perspective: these constants emerge as stable statistical solutions within a network of fluctuating wormholes, where spacetime wormhole-connectors self-organize into preferred structures, akin to equilibrium configurations in statistical mechanics.

## 3.3 The Foam-Plexus Framework and Self-Organizing Constants

The quantum foam consists of a fluctuating network of Planck-scale wormholes with an maximum density of  $N \sim 10^{99} \text{cm}^{-3}$ . This foam forms distinct Plexuses associated with fundamental forces. The emergence of physical constants can be understood in the following framework:

### 3.3.1 Statistical Equilibrium of Wormhole Networks

Each Plexus stabilizes at a preferred density  $\rho_P$  and connectivity  $C_P$ , leading to emergent force strengths. The fundamental constants arise as equilibrium values of the system.

For example, the fine-structure constant may be determined by the EM-Plexus density:

$$\alpha \sim \frac{e^2}{\hbar c} \sim \frac{\rho_{\text{EM-Plexus}}}{\rho_{\text{Total}}}. \quad (3.1)$$

Similarly, the gravitational constant depends on the Gravity-Plexus density:

$$G \sim \frac{1}{\rho_{\text{Gravity-Plexus}} L_P^2}. \quad (3.2)$$

This suggests that gravity is not an arbitrary force but emerges from the large-scale statistical connectivity of spacetime wormholes.

### 3.4 Cosmological Constant as a Stability Condition

The cosmological constant  $\Lambda$  is a major mystery in physics, with its observed value being far smaller than naive quantum field theory estimates. In the Foam-Plexus model:

$$\Lambda \sim \frac{\rho_{\text{Gravity-Plexus}}}{\rho_{\text{Vacuum}}} \cdot \frac{c^2}{L_P^2}. \quad (3.3)$$

Here,  $\Lambda$  naturally emerges from the balance between the Gravity-Plexus and quantum vacuum fluctuations, suggesting that its value is an attractor within the self-organizing structure of spacetime. Another result from designing particle structures even suggests why the current Cosmological Constant Problem isn't a problem when calculated properly.

### 3.5 Why Only These Plexuses?

A natural question arises: why do we observe only five fundamental interactions? The Foam-Plexus model suggests that only a handful of stable wormhole network configurations can persist. Basically these are the configurations that can survive and renew where others fail.

- Analogous to how only certain molecules (like DNA) form stable, self-replicating structures, only a limited number of Plexuses achieve equilibrium.
- Unstable configurations may exist temporarily but decay, leaving behind only EM, Weak, Strong, and Gravity Plexuses.

This perspective suggests that the fundamental forces we observe are not arbitrary but the only possible mutually stable solutions within the quantum foam.

### 3.6 Experimental Implications and Tests

If physical constants emerge from self-organizing spacetime structures, their values may subtly shift in extreme environments:

- **High-Energy Tests:** The fine-structure constant  $\alpha$  might vary slightly near Planck-scale interactions.
- **Gravitational Lensing Fluctuations:** If  $G$  is tied to Plexus density, minute variations may occur in strong gravitational fields.
- **Dark Energy Evolution:** The cosmological constant  $\Lambda$  could show slow evolution over cosmic time.

Future precision tests in quantum optics, gravitational wave interferometry, and cosmology may reveal subtle deviations from fixed fundamental constants.

### 3.7 Conclusion: Constants as the "DNA" of Spacetime

The Foam-Plexus model reframes physical constants as **not arbitrary** but **emergent statistical attractors** in a self-organizing quantum foam. Just as DNA encodes biological information, the stable configurations of Plexuses encode the fundamental interactions of physics. This perspective aligns quantum mechanics, general relativity, and cosmology in a unified framework where the universe's fundamental constants arise as the only stable solution to the underlying structure of spacetime itself.

# 4 Renormalization, Lagrangian, Gauge

## 4.1 Abstract

In this chapter, we explore how the Wormhole-Plexus framework inherently avoids the need for renormalization. We demonstrate that:

- quantized spacetime imposes a natural UV cutoff
- finite wormhole energies bound virtual particle contributions
- statistical mechanics ensures emergent finite amplitudes
- gauge-like dynamics maintain finite couplings
- extended topological structures eliminate point-like singularities.

Using case studies like Møller scattering and the Lamb shift, we illustrate how the model reproduces QED predictions while introducing finite, testable corrections.

## 4.2 Introduction

Renormalization is a cornerstone of modern quantum field theory (QFT), addressing ultraviolet (UV) divergences that arise in loop integrals when computing quantum corrections [8].

In quantum electrodynamics (QED), processes like electron self-energy, vertex corrections, and vacuum polarization produce divergences due to integrations over infinite momenta. Solutions require regularization and counterterms to absorb infinities into physical parameters such as mass and charge [7]. Though seemingly effective, renormalization introduces mathematical ambiguities and lacks a clear physical justification.

Traditionally, charge is treated as a fundamental property with no deeper explanation beyond its observed interactions. However, in the wormhole-plexus framework, charge emerges from topological configurations of the particles themselves.

## 4.3 The Wormhole Plexus as a Gauge Theory

### 4.3.1 Wormhole Dynamics and Curvature Emergence

In the foam-plexus model, wormholes do not individually exhibit curvature but, in aggregate, produce emergent macroscopic curvature through collective directional alignment. This is mathematically analogous to gauge fields in Yang-Mills theories, where field strength tensors encode nontrivial geometric information.

The local wormhole density for a given plexus (e.g., EM-plexus for electromagnetism) is denoted as  $\rho_w(x)$ , with specific densities  $\rho_w^e$ ,  $\rho_w^s$ , and  $\rho_w^w$  for the electromagnetic, strong, and weak interactions, respectively. The connectivity of wormholes is described by an effective potential  $W_\mu$ , which represents the collective influence of wormhole alignments. We define a field strength tensor analogous to gauge fields:

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + g[W_\mu, W_\nu],$$

where  $g$  is a coupling constant representing the strength of wormhole interactions, and the commutator  $[W_\mu, W_\nu]$  introduces nonlinearity, mirroring non-Abelian gauge theories like QCD. For Abelian interactions (e.g.,  $U(1)$  electromagnetism), the commutator vanishes ( $[W_\mu, W_\nu] = 0$ ), simplifying to a form akin to the electromagnetic field strength tensor  $F_{\mu\nu}$ .

The relation between  $\rho_w$  and  $W_\mu$  arises from wormhole density gradients. For example, in the EM-plexus, the electric field emerges as:

$$E_i = k_e \partial_i \rho_w^e,$$

where  $k_e$  is a calibration constant. The effective potential  $W_\mu$  is related to  $\rho_w$  via a statistical average over wormhole directions  $\langle \mathbf{d}_w \rangle$ , such that  $W_i \propto \langle \mathbf{d}_w \rangle \cdot \nabla \rho_w$ , capturing the directional flow of wormhole connections.

### 4.3.2 Emergence of the Standard Model Gauge Group

The gauge symmetries of the Standard Model— $U(1) \times SU(2) \times SU(3)$ —are typically imposed as abstract principles governing the fundamental interactions. In the Wormhole Plexus framework, however, these symmetries emerge naturally from the discrete topological structure of spacetime and the internal geometry of particle configurations. Fermions are not point-like but possess structured interiors composed of stable wormhole loops, whose face-specific perimeter flows give rise to the fundamental charges and couplings. Each face on a particle's polyhedral structure (explored in detail in the next chapter) corresponds to a distinct interaction channel, and its associated flux dynamically couples to the surrounding Plexus.

We outline below how each gauge group arises from this framework:

- **$U(1)$  Electromagnetism:** The electromagnetic  $U(1)$  gauge symmetry emerges from fluctuations in the EM-Plexus, driven by face-localized perimeter flows within the tetrahedral structure of charged leptons. These structured flows perturb the local wormhole density  $\rho_w^e$ , modeled as:

$$\rho_w^e(\mathbf{r}, t) = \rho_0 + \mathcal{R}_e \tau_e \frac{Aq(t)}{|\mathbf{r} - \mathbf{r}_q(t)|} e^{-\alpha|\mathbf{r} - \mathbf{r}_q(t)|},$$

where  $\rho_0$  is the ambient wormhole density, and the exponential decay reflects the limited spatial reach of a particle's structured EM face. The gradient  $\nabla \rho_w^e$  defines an effective vector potential  $A_\mu$ , and the induced field strength  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$  mirrors the Abelian structure of QED. The coupling strength  $g$  is not imposed but arises from the alignment rate and turnover time of wormholes interacting with the charged face, with:

$$g \sim k_e \mathcal{R}_e \tau_e A = \frac{1}{4\pi\epsilon_0}.$$

- **$SU(2)$  Weak Interactions:** The weak interaction's  $SU(2)$  gauge symmetry emerges from chiral asymmetries in the polyhedral faces associated with the Weak-Higgs Plexus. In fermions, especially leptons, the relative alignment of the Higgs and Weak faces encodes chirality  $\chi$ , biasing wormhole loops into left-handed or right-handed configurations. Left-handed loops ( $\chi < 0$ ) couple preferentially to the surrounding plexus, producing a triplet of emergent gauge fields  $W_\mu^a$  ( $a = 1, 2, 3$ ). These obey the non-Abelian field strength tensor:

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_w \epsilon^{abc} W_\mu^b W_\nu^c,$$

where  $g_w$  is the weak coupling constant. The parity-violating structure of the Standard Model is a direct consequence of asymmetric loop coupling driven by geometric bias in the particle's internal structure.

- **$SU(3)$  Strong Interactions:** The color interaction arises from quark pentahedrons, whose dedicated color face supports multiple simultaneous wormhole flows. These flows encode triplet configurations corresponding to red, green, and blue color charges, each realized by a different loop alignment within the strong face. Perturbations in the strong wormhole density  $\rho_w^s$  induce eight emergent gluon fields  $G_\mu^a$ , forming an  $SU(3)$  gauge structure:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc} G_\mu^b G_\nu^c,$$

where  $f^{abc}$  are the structure constants of  $SU(3)$ . The non-Abelian nature of QCD reflects the entangled flux geometry within the color face, which naturally supports gluon self-interactions and confinement via wormhole saturation.

In all cases, the gauge fields  $A_\mu$ ,  $W_\mu^a$ , and  $G_\mu^a$  are not externally imposed but arise as collective excitations in the wormhole network, seeded and shaped by the internal geometry of the particles themselves. The symmetries of the Standard Model thus reflect the structured, topological dynamics of matter embedded within quantized spacetime foam.

### 4.3.3 Avoiding Renormalization Through Discrete Dynamics

The gauge-theoretic formulation of the Wormhole Plexus naturally avoids renormalization by leveraging the discrete nature of spacetime and the finite dynamics of wormholes. Here, we outline key mechanisms:

- **Discrete Spacetime Lattice as a UV Cutoff:** The quantized lattice imposes a maximum momentum  $p_{\max} \sim \hbar/\ell_P$ , converting loop integrals into finite sums over lattice modes. For example, in a gauge loop (e.g., photon self-energy), the integral  $\int d^4k$  becomes a sum  $\sum_{\mathbf{k}}$ , with  $k \leq p_{\max}$ , eliminating UV divergences.
- **Finite Wormhole Energies:** Virtual particles (e.g., photons, gluons) are transient  $E_w$  flows with energies  $\Delta E \sim \hbar/\tau_e$ , where  $\tau_e \sim 10^{-43}$  s at the Planck scale. This bounds contributions in loop diagrams, ensuring finite corrections (e.g.,  $\Delta E/E \sim 10^{-20}$ ).
- **Statistical Mechanics and Emergent Amplitudes:** Amplitudes are computed by summing over finite plexus configurations, weighted by path probabilities  $\psi_i \propto e^{-r_i/\ell_P} e^{iE_w t/\hbar}$ , avoiding infinite corrections.
- **Gauge-Like Dynamics with Finite Couplings:** The couplings  $g$ ,  $g_w$ , and  $g_s$  are tied to wormhole realignment probabilities, remaining finite due to lattice discreteness, unlike QFT where couplings run to infinity at high energies.
- **Extended Topological Structures:** Particles are extended wormhole loops (e.g.,  $L_w \sim 10^{-10}$  m for electrons), eliminating point-like singularities and ensuring finite self-energies.

These mechanisms ensure that the gauge-theoretic Wormhole Plexus avoids renormalization while reproducing standard QFT results at low energies.

## 4.4 The Lagrangian for the Wormhole-Plexus

To formalize the dynamics of the Wormhole Plexus, we construct a Lagrangian incorporating the kinetic terms of the wormhole field  $W_\mu$ , interaction terms from wormhole density perturbations, and couplings reproducing Standard Model interactions. The general form of the Lagrangian is:

$$\mathcal{L} = -\frac{1}{4}W^{\mu\nu}W_{\mu\nu} + \sum_i \bar{\psi}_i(i\gamma^\mu D_\mu - m_i)\psi_i + \mathcal{L}_{\text{int}},$$

where  $W_{\mu\nu}$  is the field strength tensor,  $\psi_i$  represents fermion fields (e.g., quarks, leptons),  $D_\mu$  is the covariant derivative, and  $\mathcal{L}_{\text{int}}$  encodes emergent interactions.

### 4.4.1 Covariant Derivative and Gauge Couplings

The covariant derivative  $D_\mu$  incorporates the gauge structure of the emergent fields:

$$D_\mu = \partial_\mu - ieA_\mu - ig_w \frac{\sigma^a}{2} W_\mu^a - ig_s \frac{\lambda^a}{2} G_\mu^a,$$

where  $e$ ,  $g_w$ , and  $g_s$  are the coupling constants for  $U(1)$ ,  $SU(2)$ , and  $SU(3)$ , respectively;  $\sigma^a$  are the Pauli matrices for  $SU(2)$ ; and  $\lambda^a$  are the Gell-Mann matrices for  $SU(3)$ . The fields  $A_\mu$ ,  $W_\mu^a$ , and  $G_\mu^a$  correspond to the photon, weak bosons, and gluons, respectively, but are interpreted as collective modes of wormhole alignments.

The coupling constants are calibrated to match Standard Model values at low energies. For example,  $e$  relates to the fine structure constant  $\alpha \approx 1/137$ , while  $g_w$  and  $g_s$  are determined by weak and strong interaction strengths. Their finiteness arises from the discrete lattice, as wormhole realignment probabilities are bounded by the finite number of quanta ( $N \sim 10^{99} \text{ cm}^{-3}$ ).

### 4.4.2 Interaction Terms

The interaction term  $\mathcal{L}_{\text{int}}$  encodes emergent Standard Model interactions arising from wormhole realignment processes. We decompose it as:

$$\mathcal{L}_{\text{int}} = \mathcal{L}_{\text{QED}} + \mathcal{L}_{\text{weak}} + \mathcal{L}_{\text{QCD}},$$

where each term corresponds to interactions mediated by  $A_\mu$ ,  $W_\mu^a$ , and  $G_\mu^a$ , respectively. For example:

**QED Interactions:** The electromagnetic interaction arises from fermion couplings to  $A_\mu$ , modeled as:

$$\mathcal{L}_{\text{QED}} = -e\bar{\psi}\gamma^\mu A_\mu\psi,$$

where  $\psi$  represents charged fermions (e.g., electrons). In the plexus, this term emerges from wormhole density perturbations  $\rho_w^e$ , with  $A_\mu \propto \partial_\mu \rho_w^e$ .

**Weak Interactions:** The weak interaction includes terms like:

$$\mathcal{L}_{\text{weak}} = -\frac{g_w}{\sqrt{2}}\bar{\psi}_L\gamma^\mu W_\mu^+\nu_L + \text{h.c.},$$

where  $\psi_L$  and  $\nu_L$  are left-handed fermions and neutrinos, reflecting the chiral asymmetry of wormhole loops (Section 2.2). The coupling arises from wormhole realignment probabilities biased by chirality  $\chi$ .

**QCD Interactions:** The strong interaction includes quark-gluon couplings and gluon self-interactions:

$$\mathcal{L}_{\text{QCD}} = -g_s\bar{q}\gamma^\mu\frac{\lambda^a}{2}G_\mu^aq - \frac{1}{4}g_sf^{abc}G_\mu^aG_\nu^b\partial^\mu G^{\nu c},$$

where  $q$  are quark fields, and the second term represents the three-gluon vertex. In the plexus, this emerges from triplet alignments of wormhole loops in the Strong-plexus, with  $f^{abc}$  reflecting the multiplicity of color configurations.

These interaction terms are derived from stochastic realignment of wormholes at overlap points, where the probability of realignment  $P_{\text{realign}} \propto \mathcal{R}\tau$  (with  $\mathcal{R}$ ,  $\tau$  as formation rate and turnover time) determines the effective coupling strength.

#### 4.4.3 Gauge Invariance and Wormhole Topology

The Lagrangian is gauge-invariant under transformations of  $A_\mu$ ,  $W_\mu^a$ , and  $G_\mu^a$ , reflecting the underlying topological stability of the wormhole network. For instance, a  $U(1)$  gauge transformation  $A_\mu \rightarrow A_\mu + \partial_\mu\lambda$  corresponds to a global shift in wormhole alignment phases, which leaves  $\rho_w^e$  gradients unchanged. Similarly,  $SU(2)$  and  $SU(3)$  transformations adjust the chirality and color configurations of wormhole loops without altering physical observables.

### 4.5 Case Studies

To illustrate how the Wormhole Plexus reproduces QED results while avoiding renormalization, we revisit two case studies from earlier.

#### 4.5.1 Møller Scattering

In Møller scattering ( $e^-e^- \rightarrow e^-e^-$ ), standard QED computes tree-level and loop amplitudes, with divergences in loops requiring renormalization [8]. In the plexus model:

- **Tree-level:** The virtual photon exchange corresponds to a transient  $\Delta\rho_w^e$ , propagating via a discrete connectivity function  $G(x, x') = Ce^{-|x-x'|/\ell_P}$ . The amplitude matches QED but avoids divergent vertex corrections due to finite  $\Delta\rho_w^e$ .
- **Loop Corrections:** Nested  $\Delta\rho_w^e$  fluctuations (e.g., vacuum polarization) are finite due to lattice discreteness, summing over  $k \leq p_{\text{max}}$ .
- **Prediction:** Lattice-induced scattering asymmetry  $\Delta\sigma/\sigma \sim 10^{-5}$ , detectable at high-precision facilities like LHC [3].

#### 4.5.2 Lamb Shift

The Lamb shift in QED involves divergent self-energy and vacuum polarization, requiring renormalization [8]. In the plexus model:

- Corrections arise from finite  $\Delta\rho_w^e$ , with  $\Delta E \sim \hbar/\tau_e$ , where  $\tau_e \sim 10^{-21}$  s for electron-related processes.
- Prediction: Deviation  $\Delta E/E \sim 10^{-20}$ , testable with ultra-precision spectroscopy [4].

## 4.6 Implications and Experimental Predictions

### 4.6.1 Theoretical Implications

The Wormhole Plexus framework provides a physically motivated alternative to standard renormalization techniques:

- **Finite Corrections:** All quantum corrections are finite, eliminating counterterms.
- **Gauge Unification:** The natural emergence of  $U(1) \times SU(2) \times SU(3)$  from wormhole dynamics offers a topological basis for Standard Model symmetries.

### 4.6.2 Experimental Predictions

The model introduces finite corrections testable with precision experiments:

- **Scattering Asymmetries:** Lattice discreteness induces  $\Delta\sigma/\sigma \sim 10^{-5}$  in processes like Møller scattering, detectable at LHC or future lepton colliders (e.g., ILC) [3].
- **Lamb Shift Deviations:** Finite  $\Delta\rho_w^e$  predicts  $\Delta E/E \sim 10^{-20}$ , testable with hydrogen spectroscopy experiments [4].
- **Gravitational Wave Noise:** Plexus fluctuations coupling to the Gravity-plexus induce perturbations  $\Delta h/h \sim 10^{-5}$ , testable with the Einstein Telescope [27].
- **Gauge Coupling Deviations:** The running of gauge couplings (e.g.,  $\alpha$ ,  $\alpha_s$ ) may exhibit deviations  $\Delta\alpha/\alpha \sim 10^{-5}$  at high energies, measurable at LHC or future colliders [6].

## 4.7 Challenges and Future Directions

### 4.7.1 Quantitative Loop Calculations

Explicitly computing loop corrections in the gauge-theoretic framework could provide numerical benchmarks, comparing finite corrections to QFT's divergent ones.

### 4.7.2 High-Energy Behavior

Exploring the behavior of gauge amplitudes near Planck-scale energies could validate the model's consistency, potentially revealing new phenomena.

### 4.7.3 Experimental Sensitivity

Ensuring predicted deviations are distinguishable from QFT corrections requires precise experimental design, potentially necessitating new facilities beyond current LHC capabilities.

## 4.8 Conclusion

The Wormhole Plexus model in Cassiopeia's ToE avoids renormalization by leveraging a discrete spacetime lattice, finite wormhole energies, statistical mechanics, gauge-like dynamics, and extended topological structures. Formulating the plexus as a gauge theory, we derive the Standard Model gauge group  $U(1) \times SU(2) \times SU(3)$  from wormhole dynamics and construct a Lagrangian capturing its interactions. Case studies like Møller scattering and the Lamb shift illustrate finite corrections (e.g.,  $\Delta\sigma/\sigma \sim 10^{-5}$ ,  $\Delta E/E \sim 10^{-20}$ ), avoiding counterterms. This approach offers a physically grounded alternative to QFT's continuum assumptions, aligning with Cassiopeia's ToE's goal of unifying relativity and quantum mechanics through quantized spacetime. Testable predictions invite empirical validation of Planck-scale physics in fundamental interactions.

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# 5 Particle Structure and Statistics

## 5.1 Charge as Angular Momentum in the Quantum Foam

In Cassiopeia’s Foam–Plexus Theory of Everything, charge emerges not as an intrinsic label but as a consequence of angular momentum flows through discrete spacetime. The universe is composed of quantized foam, a lattice of Planck-scale sites connected by transient wormholes. These wormholes carry angular momentum in closed paths, forming the foundation of particle structure.

**Charge conservation** arises naturally as conservation of angular momentum within the foam:

$$Q \propto \frac{e}{\hbar} \oint \vec{L}_{\text{foam}} \cdot d\vec{\ell}, \quad (5.1)$$

where  $\vec{L}_{\text{foam}}$  is the angular momentum density of wormhole flux circulating around a polyhedral perimeter. A fixed proportionality sets the quantum of charge in terms of the fundamental angular-momentum quantum carried by a perimeter loop.

We recognize that the loops / faces are responsible for the various wormhole plexuses. A particle must have at least one loop for each plexus that it generates. Leptons therefore have four faces—one each for Gravity, Electromagnetism, Weak, and Higgs—and quarks have five faces, adding a Strong (color) face. The simplest structures to visualize are tetrahedrons for leptons and pentahedrons for quarks.

Each face of a polyhedral fermion hosts a closed perimeter loop. These flows do not merely couple to known forces; they *generate* each force’s associated Plexus via the **stochastic emergence of wormholes**. Each emergent wormhole behaves as a virtual boson of that force. Only a fraction of these wormholes rejoin the face’s closed loop. Most radiate outward over a  $4\pi$  steradian field before decaying back into the foam:

$$P(\text{rejoin}) \ll P(\text{radiate}). \quad (5.2)$$

This outward spray generates the corresponding field around the particle, explaining the physical reach of forces. Gravitational wormholes emitted from the G face feed the Gravity–Plexus, which acts as a universal topological gradient biasing all plexus interactions.

## 5.2 Fermions as Polyhedra

### Tetrahedral Structure for Leptons

We suggest that leptons form as tetrahedrons with four triangular faces, each responsible for one force: Gravity (G), Electromagnetic (EM), Weak (W), and Higgs (H). Edges are shared between faces, enabling flux coupling.

Each triangular face can be subdivided into three subtriangles, each supporting a portion of the total flux. The flows around these perimeters are quantized and directional.

**Chirality** is determined not by the gross orientation of the tetrahedron but by the **relative flow direction between the W and H faces**. If these flows align, the particle is strongly coupled to mass (e.g., the electron). If they oppose, mass coupling is suppressed (e.g., the neutrino).

#### 5.2.1 The Electron Tetrahedron

- All four faces active: G, EM, W, H.
- EM face subdivided into three inward-pointing flows:

$$q_{\text{EM}} = \sum_{i=1}^3 q_i = -\frac{1}{3}e - \frac{1}{3}e - \frac{1}{3}e = -e. \quad (5.3)$$

- W and H flows aligned: **strong mass coupling**.
- Generates full-strength EM and weak fields.

### 5.2.2 The Neutrino Tetrahedron

- All faces present, including EM.
- EM subtriangle flows:  $-\frac{1}{3}e$ ,  $-\frac{1}{3}e$ ,  $+\frac{2}{3}e$ .
- Total charge cancels:

$$q_{\text{EM}} = -\frac{1}{3}e - \frac{1}{3}e + \frac{2}{3}e = 0. \quad (5.4)$$

- W and H flows **oppose**: minimal mass coupling.
- Produces only a weak field; EM and H fields are strongly suppressed.

### 5.2.3 Fractal Faces and Lepton Families

Each face can recurse into deeper subtriangles, generating the higher lepton families:

$$m_f \propto \sum_{n=1}^N 3^n E_{\text{sub},n}, \quad (5.5)$$

where  $E_{\text{sub},n}$  is the characteristic energy associated with subloops at level  $n$ . Higher  $n$  leads to increased flux and energy, producing heavier muon and tau structures.

## 5.3 Quarks as Pentahedrons

### 5.3.1 Geometry and Force Coupling

Quarks adopt a five-face structure—four triangles (G, W, H, and Strong/Color) and one **quadrilateral EM face**. This geometry allows diagonal wormhole paths across the EM face, enabling fractional charge.

### 5.3.2 Fractional Charge from EM Face Geometry

- Quadrilateral EM face supports four diagonals.
- Each diagonal contributes  $\pm\frac{1}{3}e$  worth of EM flux.
- Up quark (two aligned diagonals):

$$q = +\frac{2}{3}e. \quad (5.6)$$

- Down quark (one diagonal):

$$q = -\frac{1}{3}e. \quad (5.7)$$

This fractional structure is stabilized by the Strong face's recursive color-loop geometry. The Strong face is a quadrilateral subdivided into eight gluon subloops, naturally organizing the SU(3) color degrees of freedom and helping suppress strong CP violation through geometric symmetry.

## 5.4 Bosons as Double Wormhole Loops

### General Structure

Bosons form from two oppositely or complementarily circulating wormhole loops. These double-loop structures do not include a Gravity face—bosons *follow* but do not *source* gravity.

### Gravitational vs. Inertial Mass in the Foam–Plexus

In Cassiopeia’s model, the classical equivalence between gravitational and inertial mass breaks down at the fundamental level.

**Fermions** include a Gravity face. Their perimeter flows stochastically emit gravitational wormholes that radiate outward, forming real spacetime curvature: they possess inertial mass and actively *source* the Gravity–Plexus.

**Bosons**, however, lack a Gravity face. Though they may exhibit inertial mass due to internal loop tension (e.g.,  $W$  and Higgs bosons), they do not radiate gravitational wormholes and therefore do not *source* spacetime curvature. They still follow the curvature generated by fermionic Gravity faces, via biased wormhole hand-offs in the Gravity–Plexus density gradient.

This leads to a critical consequence: **free bosons in the vacuum—such as photons, gluons, and virtual pairs—do not contribute to the *sourcing* of the gravitational energy of space.** Their energy density exists, but is gravitationally silent at the level of curvature generation.

### Cosmological Constant Implication

This distinction provides a natural solution to the longstanding cosmological constant problem. In standard quantum field theory, the vacuum energy from all virtual bosons predicts a spacetime curvature many orders of magnitude larger than observed.

In the Foam–Plexus framework, this vacuum energy—though real—is *gravitationally silent*. Only wormhole emissions from fermionic Gravity faces contribute to spacetime curvature. Thus, the enormous energy density of free-space virtual bosons does not inflate the universe, neatly resolving the discrepancy between QFT vacuum estimates and the observed dark-energy scale.

### Spin and Quantum Statistics

The structural differences between fermions and bosons in the Foam–Plexus model also explain the origin of quantum spin and particle statistics.

**Fermions**, built from closed polyhedral structures, contain wormhole fluxes that invert under a  $360^\circ$  rotation:

$$\psi \rightarrow -\psi, \quad (5.8)$$

and only after a  $720^\circ$  rotation does the particle return to its original quantum state:

$$\psi \rightarrow +\psi. \quad (5.9)$$

This topological inversion defines spin- $\frac{1}{2}$  behavior and enforces antisymmetric wavefunctions under particle exchange:

$$\psi_1\psi_2 - \psi_2\psi_1 = 0. \quad (5.10)$$

This is the origin of the Pauli exclusion principle in the Foam–Plexus picture.

**Bosons**, composed of double-loop wormhole structures, do not undergo sign inversion under a  $360^\circ$  rotation. Their flux configuration remains invariant:

$$\psi \rightarrow \psi. \quad (5.11)$$

Thus, bosons obey symmetric wavefunctions and Bose–Einstein statistics:

$$\psi_1\psi_2 + \psi_2\psi_1, \quad (5.12)$$

allowing many bosons to occupy the same state.

#### 5.4.1 Photon

- Two EM loops, opposite circulation.
- $q = 0$ , spin-1.
- No Gravity face: does not *source* curvature, but its EM wormhole renewals are biased by Gravity–Plexus density gradients, so it follows curved null geodesics (lensing, Shapiro delay, Kerr orbits).

### 5.4.2 $W^\pm$ Bosons

- One Weak–Higgs (WH) loop + one EM loop.
- $q = \pm e$ , spin-1.
- Massive due to WH loop tension and W–H coupling.

### 5.4.3 $Z$ Boson

- Two Weak–Higgs loops with EM contributions canceling.
- $q = 0$ , spin-1.
- Massive from WH loop tension.

### 5.4.4 Gluons

- Two color loops (e.g., red–antiblu).
- $q = 0$ , spin-1.
- Confined via color topology in the Strong face.

### 5.4.5 Higgs Boson

- Two Weak loops in-phase (pure WH scalar excitation).
- Spin-0 (scalar),  $q = 0$ .
- Confirms the dynamical reality of the Higgs plexus that sets fermion mass rules.

## 5.5 Unified View

The Foam–Plexus model recasts the Standard Model as a necessary outcome of geometry:

- **Charge:** angular momentum in EM perimeter loops.
- **Mass:** W–H flow alignment and WH loop tension.
- **Spin:** reversal (or non-reversal) of wormhole flux under  $720^\circ$  (or  $360^\circ$ ) rotation.
- **Chirality:** W flow direction relative to H flow on tetrahedral faces.
- **Gravity:** stochastic emission of G-face wormholes, feeding a universal Gravity–Plexus gradient.

Fermions form stable polyhedra with Gravity faces; bosons are radiative double loops without Gravity faces. The universe is structured, quantized, and rich in testable geometric foundations.

### 5.5.1 Parity and CP Violation from Polyhedral Geometry

In the Foam–Plexus framework, parity (P) and charge conjugation (C) have clear geometric interpretations:

- **Parity (P)** inverts spatial geometry. In a polyhedron, this effectively **swaps or reflects faces**, particularly interchanging spatially-defined interactions (e.g., left-handed Weak and right-handed Higgs faces).
- **Charge conjugation (C)** reverses the direction of all perimeter wormhole flows. Each flux loop changes sign:

$$Q_i \rightarrow -Q_i, \quad \vec{d}_w^i \rightarrow -\vec{d}_w^i. \quad (5.13)$$

- **CP** acts jointly, reflecting the shape and inverting the flows.

Because each face in the tetrahedron or pentahedron defines not just a location but a *directional flow*, these transformations are not always symmetric. For example:

- In neutrinos, the W face flows upward, while the H face flows downward. Under CP, these flows reverse, but the edge junctions—where W and H flows interfere—**do not return to their original structure**.
- The resulting configuration can have different stability or field-emission properties. Thus, CP violation arises not as an arbitrary probabilistic asymmetry but from **non-recoverable geometric differences**.

This helps explain why:

- Neutrinos are only observed as left-handed.
- CP violation appears strongly in the Weak sector but not in EM or Gravity.
- Pentahedral quarks—with more complex EM and Strong faces—exhibit small CP violations in certain meson decays.

In this view, CP violation is not exotic. It is an **inevitable outcome of asymmetrical edge reconfiguration** under fundamental operations on geometric flow structures. The model thus offers a visual, structural basis for one of the Standard Model's deepest mysteries and dovetails with the more detailed CP-violation analysis in later chapters.

# 6 Chiral Superposition of Particle States

## 6.1 Abstract

In the Standard Model (SM), physical particles like the electron are superpositions of left- and right-handed chiral states, with only the left-handed component participating in charged-current weak interactions. Within Cassiopeia’s Theory of Everything (ToE), spacetime is a quantized lattice of discrete quanta connected by dynamic wormholes forming plexuses, offering a quantum-topological reinterpretation. This paper proposes that chiral states are encoded as topological properties (chirality  $\chi$ ) of wormhole loops, with physical particles as superpositions of  $\chi = -1$  (left-handed) and  $\chi = +1$  (right-handed) states. Selective coupling to the Weak-plexus ( $\chi = -1$ ) mirrors the SM’s V-A structure, while nonlocal correlations and Planck-scale granularity introduce deviations. Using muon decay ( $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ ) as a case study, we explore how chiral superposition manifests in wormhole topology, predicting testable effects like polarization asymmetries ( $\Delta P/P \sim 10^{-5}$ ), decay rate shifts ( $\Delta\tau/\tau \sim 10^{-5}$ ), and angular distribution anomalies ( $\Delta\theta/\theta \sim 10^{-5}$ ). This framework bridges particle chirality with quantized spacetime, enriching Cassiopeia’s ToE and inviting empirical validation.

## 6.2 Introduction

In the Standard Model (SM), particles like the electron are described as superpositions of left- and right-handed chiral states, with only the left-handed component coupling to charged-current weak interactions [7]. The electron’s Dirac spinor  $\psi = \psi_L + \psi_R$ , where  $\psi_L$  and  $\psi_R$  are eigenstates of the chirality operator  $\gamma^5$ , evolves dynamically, with mass terms mixing chiralities via the Higgs mechanism. The V-A (vector minus axial-vector) structure of weak interactions ensures only  $\psi_L$  (and right-handed antifermions) participate in charged-current processes, as seen in decays like  $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ , where outgoing electrons are preferentially left-handed [8].

Cassiopeia’s Theory of Everything (ToE) reimagines spacetime as a quantized lattice of discrete quanta ( $N \sim 10^{99} \text{ cm}^{-3}$ ) at the Planck scale ( $\ell_P \sim 10^{-35} \text{ m}$ ), interconnected by dynamic wormholes forming specialized plexuses (e.g., EM-, Strong-, Weak-, Higgs-, Gravity-plexus). Particles are stable wormhole loops, with properties encoded topologically. Previous works have modeled quantum mechanics, decays, and weak interactions via these plexuses.

This paper proposes that chiral states are topological features of wormhole loops—left-handed ( $\chi = -1$ ), right-handed ( $\chi = +1$ )—with physical particles as superpositions. Selective Weak-plexus coupling ( $\chi = -1$ ) mirrors SM chirality, while nonlocal correlations and Planck-scale effects introduce deviations. Using muon decay as a case study, we explore this superposition, predicting polarization asymmetries ( $\Delta P/P \sim 10^{-5}$ ), decay rate shifts ( $\Delta\tau/\tau \sim 10^{-5}$ ), and angular distribution anomalies ( $\Delta\theta/\theta \sim 10^{-5}$ ). This bridges particle chirality with quantized spacetime, advancing Cassiopeia’s ToE.

## 6.3 Chiral Superposition in the Standard Model

### 6.3.1 Chirality and Superposition

In the SM, a Dirac fermion (e.g., electron) is a superposition of chiral states:

$$\psi = \psi_L + \psi_R, \quad \psi_L = \frac{1 - \gamma^5}{2} \psi, \quad \psi_R = \frac{1 + \gamma^5}{2} \psi,$$

where  $\gamma^5 \psi_L = -\psi_L$ ,  $\gamma^5 \psi_R = +\psi_R$ . Mass mixes these via  $m_e \bar{\psi} \psi = m_e (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$ , requiring the Higgs mechanism [7].

### 6.3.2 Weak Interactions

Charged-current weak interactions couple only to  $\psi_L$ :

$$\mathcal{L}_{\text{weak}} \supset \frac{g}{\sqrt{2}} \bar{\psi}_L \gamma^\mu W_\mu^- \nu_L + \text{h.c.},$$

e.g., in muon decay, the electron is preferentially left-handed [8].

## 6.4 Wormhole Plexus Framework and Chiral States

### 6.4.1 Wormhole Loops

In Cassiopeia's ToE, the plexus generators are stable but different wormhole loops for the various plexuses:  
 - Electron loop:  $L_w \sim 10^{-10}$  m,  $\rho_w^e \propto |\psi|^2$ , phase  $S$ . - Resides in EM-, Weak-, Higgs-plexuses for interactions.

### 6.4.2 Chiral Encoding

Chirality  $\chi$ : topological twist of the loop: -  $\chi = -1$ : Left-handed, specific twist. -  $\chi = +1$ : Right-handed, opposite twist. Superposition: Loop as  $\psi = \psi_L + \psi_R$ , probabilities over  $\chi = \pm 1$ .

### 6.4.3 Weak-Plexus Coupling

Weak-plexus ( $L_w \sim 10^{-18}$  m) couples to  $\chi = -1$ , mediating W/Z  $E_w$  flows.

## 6.5 Mapping Chiral Superposition to Wormhole Plexus

### 6.5.1 Electron as Superposition

Electron loop: Superposition of  $\chi = -1$ ,  $\chi = +1$ : -  $\psi_L \rightarrow \chi = -1$ , aligns with Weak-plexus. -  $\psi_R \rightarrow \chi = +1$ , weak-inert.

### 6.5.2 Weak Interaction Selectivity

Weak-plexus couples to  $\chi = -1$ , projecting loop onto left-handed state during processes.

### 6.5.3 Higgs-Plexus Mixing

Higgs-plexus mixes  $\chi = \pm 1$ , adjusting  $\rho_w^H$ , providing mass.

## 6.6 Case Study: Muon Decay

$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ , SM  $\tau \approx 2.2 \times 10^{-6}$  s:

### 6.6.1 SM Description

Muon ( $\psi = \psi_L + \psi_R$ ) decays via  $W^-$ , electron preferentially left-handed [8].

### 6.6.2 Wormhole Plexus Representation

1. **Muon**: Loop with  $\chi = -1, +1$ , projects to  $\chi = -1$  for weak decay. 2. **Weak-Plexus**:  $W^-$  as  $E_w$  flow, couples to  $\chi = -1$ . 3. **Higgs-Plexus**: Adjusts masses via  $\rho_w^H$ . 4. **Decay Products**: Electron, neutrinos as loops,  $\chi = -1$ . 5. **Nonlocal Effects**: Enhance correlations, shift observables.

## 6.7 Testable Predictions

### 6.7.1 Polarization Asymmetries

Nonlocal effects alter electron polarization:

$$\Delta P/P \sim 10^{-5},$$

testable in muon decay [10].

### 6.7.2 Decay Rate Shifts

Stochastic fluctuations shift rates:

$$\Delta\tau/\tau \sim 10^{-5},$$

testable with LHCb [9].

### 6.7.3 Angular Distribution Anomalies

Chirality topology induces asymmetries:

$$\Delta\theta/\theta \sim 10^{-5},$$

detectable in muon decay [10].

## 6.8 Challenges and Future Directions

### 6.8.1 Neutrino Oscillations

Neutrinos ( $\chi = -1$ ) oscillate; explore superposition effects.

### 6.8.2 High-Energy Processes

Test chirality at TeV scales [11].

### 6.8.3 Nonlocal Correlations

Quantify effects on multi-particle decays.

## 6.9 Conclusion

This paper reinterprets chiral superposition in the Wormhole Plexus model within Cassiopeia's ToE. Left- and right-handed states ( $\chi = \pm 1$ ) form superpositions in wormhole loops, with Weak-plexus coupling to  $\chi = -1$ . Muon decay illustrates this, predicting polarization asymmetries ( $\Delta P/P \sim 10^{-5}$ ), decay rate shifts ( $\Delta\tau/\tau \sim 10^{-5}$ ), and angular anomalies ( $\Delta\theta/\theta \sim 10^{-5}$ ). This bridges particle chirality with quantized spacetime, advancing Cassiopeia's ToE and inviting validation.

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## 7 Key Insights (so far)

The quantized spacetime model presented here resolves the apparent conflict between a discrete spacetime structure and Lorentz invariance. The key insights are:

- **Spacetime Quanta and Statistical Emergence:** Instead of a rigid lattice, spacetime consists of Planck-scale quanta connected via a fluctuating network of wormholes. This ensures that no fixed background or preferred frame emerges.
- **Wormhole Interactions and Field Theory:** The alignment and density fluctuations of these wormholes introduce an emergent gauge principle, leading naturally to relativistic field equations.
- **Lorentz Invariance as a Statistical Property:** While individual wormhole connections fluctuate anisotropically, large-scale statistical averaging restores Lorentz symmetry, making it an emergent property of the quantum foam.
- **Testable Predictions:** The presence of Planck-scale fluctuations suggests small but detectable deviations from classical relativity and quantum electrodynamics. These include:
  - Tiny energy-dependent shifts in the speed of light detectable in gamma-ray burst arrival times.
  - Small spatial variations in the fine-structure constant observable in high-redshift quasar spectra.
  - Subtle modifications to Maxwell’s equations testable in ultra-high-intensity QED laser experiments.
- **Experimental Outlook:** While these effects are extremely small, next-generation astrophysical and laboratory experiments may reach the required precision to test these predictions.

The preservation of Lorentz invariance across the ensemble average lays the foundation for deriving the Einstein field equations from wormhole density gradients. Thus, general relativity appears as a thermodynamic limit of a deeper, quantized network structure – a central premise for emergent gravity.

# 8 What’s Still to Come

In order to situate the Foam–Plexus framework within broader physics, we close this Foundations paper with a roadmap of how the model addresses the major unresolved issues in modern physics. This section is not a detailed derivation, but a survey: a problem-by-problem mapping that shows how Foam–Plexus resolves renormalization, singularities, the cosmological constant problem, dark matter, dark energy, quantum nonlocality, and more. Full derivations are developed in dedicated Zenodo publications, which are cited throughout.

## 8.0.1 Resolving Foundational Problems in Physics through the Foam–Plexus Model

Modern physics, while immensely successful in predictive capacity, continues to struggle with conceptual crises: ultraviolet divergences in QFT, singularities in general relativity, the cosmological constant problem, fine-tuning of parameters, unexplained symmetries, and cosmological anomalies such as the Hubble tension. The Foam–Plexus Theory of Everything proposes that spacetime itself is quantized into Planck-scale elements linked by wormholes, forming overlapping plexuses that generate forces, particles, and cosmological dynamics. Polyhedral particle structures emerge as intersections of wormhole loops, while gauge symmetries, spin, charge, and even inflation arise from the geometry and dynamics of these networks.

This section presents a problem-by-problem mapping: each major unsolved issue in physics is addressed with a Foam–Plexus mechanism, supported by dedicated Zenodo publications. The model not only avoids singularities and infinities but provides geometric origins for symmetry, unifies GR and QFT, and delivers testable predictions in cosmology and gravitational waves. The aim is clarity: to show that disparate puzzles share a single root cause—misidentifying spacetime as continuous rather than quantized.

## 8.1 Renormalization in Quantum Field Theory

Standard QFT requires renormalization because loop integrals diverge at high energies. The Foam-Plexus model eliminates this issue by imposing a fundamental lattice spacing at the Planck length ( $\ell_P \sim 10^{-35}$  m). Wormhole dynamics restrict how virtual particles propagate and bound their contributions, so enhanced Feynman diagrams remain finite without counterterms. See: Feynman Diagrams in Foam [7].

## 8.2 UV Divergences in QFT

Vacuum energy integrals diverge because conventional spacetime allows arbitrarily small wavelengths. In Foam-Plexus, wormholes behave as harmonic oscillators, with discrete energy levels  $E_n = \hbar\omega_0(n + 1/2)$ . This quantization caps contributions from high-frequency modes and resolves UV divergences without ad hoc renormalization tricks. See: Harmonic Oscillator Wormholes [5].

## 8.3 Singularities in General Relativity

GR predicts infinite curvature in black holes and the Big Bang. In Foam-Plexus, no such infinities occur. Black holes form layered event horizons where wormhole density saturates; matter never reaches a singularity but accumulates in successive shells. Cosmology begins not from a point singularity but from an eternal lattice of quanta; a quantum fluctuation spark initiates inflation without infinite density. See: Gravity Standalone [2], BEAST ToE [1].

## 8.4 Information Paradox

Each horizon layer stores information holographically, and as Hawking radiation gradually evaporates the outermost layer, information is released step by step. By the time the last horizon dissolves, the original information is fully recovered, preserving unitarity. See: Gravity Standalone [2].

## 8.5 Cosmological Constant Problem

Naively summing QFT vacuum modes overshoots the observed  $\rho_\Lambda$  by  $10^{120}$ . Foam-Plexus resolves this by excluding bosonic loops from gravitational sourcing: bosons lack a Gravity-face and do not curve spacetime. Only fermionic wormhole loops gravitate, producing a vacuum energy density of the right order of magnitude without fine-tuning. See: BEAST ToE [1], Eternal Foam Cosmology [9].

## 8.6 Dark Energy and the Hubble Tension

Dark energy is not a fixed  $\Lambda$  but an evolving effect of plexus thinning: stretched wormholes reduce binding and accelerate cosmic expansion. Relic wormhole loops contribute a clustering-dependent energy density. On galactic scales, this produces local boosts to the Hubble parameter, explaining the observed  $\sim 10\%$  tension between local and CMB values. See: Eternal Foam Cosmology [9].

## 8.7 Constant- $G$ Cosmology from a Gravity-Only Evolving Plexus

We adopt the minimal assumption that the foam (Planck substrate) is eternal and invariant, while *only* the Gravity plexus undergoes cosmological reconfiguration. This preserves the constancy of  $G$ ,  $\alpha$ , and particle masses, yet allows large-scale geometry to change through a gravity-only relic medium. In this picture, a single Gravity-face substance appears in two phases: a bound, halo-trapped phase that behaves as pressureless matter (DM-like), and an unbound, percolating phase with negative effective pressure (DE-like).

## 8.8 Dark Matter

Rather than exotic particles, dark matter is identified as a Gravity-only plexus (or relic loops) that interacts gravitationally but not electromagnetically, weakly, or strongly. The expected density in galaxies matches what is needed to explain rotation curves and lensing. See: Eternal Foam Cosmology [9].

## 8.9 Gravitational Wave Backgrounds and Mesh Noise

The Foam-Plexus model predicts distinctive gravitational wave (GW) signatures. In continuous GR, stochastic GW backgrounds are modeled with smooth spectra (e.g. power laws from inflation or astrophysical populations). In Foam-Plexus, the underlying wormhole lattice introduces discreteness and percolation statistics, modifying the expected spectrum.

### 8.9.1 GW Mesh Noise as a Distinctive Signature

A percolating gravity-only loop network predicts a broad stochastic background with a fractal-shape spectrum set by the evolving effective dimension  $D_{\text{eff}}(z)$  rather than a single power law. Next-generation detectors (ET, CE, LISA) can search for this “mesh” imprint, which differs from inflationary or purely astrophysical templates.

## 8.10 Fine-Tuning and Physical Constants

Constants like  $G$ ,  $\alpha$ , and  $\Lambda$  arise statistically from equilibrium wormhole lengths and alignments. Each plexus has oscillator modes with characteristic scales  $\ell_i = \ell_P / \sqrt{n_i}$ , producing natural hierarchies. Constants are attractors of the underlying dynamics. See: BEAST ToE [1].

## 8.11 Gauge Symmetries

Gauge symmetries arise geometrically: polyhedral fermions (tetrahedra and pentahedra) have perimeter fluxes that enforce charge quantization. Shared edges between faces encode mixing between forces. Thus

$U(1) \times SU(2) \times SU(3)$  emerges from topology, not by fiat. See: BEAST ToE (Ch. 14) [1], and extended duality treatment in String from Foam [3].

## 8.12 Unification of Forces

Leptons and quarks are polyhedra that incorporate all interactions via their faces. The Higgs, EM, weak, strong, and gravity plexuses are unified geometrically as aspects of a common wormhole-lattice substrate. See: BEAST ToE [1].

## 8.13 Spin and the Dirac Equation

Foam-Plexus derives spin-1/2 from flux reversal: a  $360^\circ$  rotation flips wormhole flows, requiring  $720^\circ$  for full restoration. Dirac's equation follows from continuity and phase dynamics of wormhole density in polyhedral structures. See: Dirac Equation from Foam Plexus [8].

## 8.14 Proton–Electron Charge Equality

Positive and negative loop fluxes are balanced by angular momentum conservation in perimeter flows, ensuring exact charge equality. See: BEAST ToE [1].

## 8.15 Matter–Antimatter Asymmetry

Biased condensation of primordial loops explains why leptons dominate over antileptons while baryons survive. This produces the observed  $\eta \sim 10^{-10}$  without requiring CP-violating decays. See: Matter–Antimatter [6].

## 8.16 Quantum Entanglement

Nonlocal entanglement emerges as wormhole oscillators synchronize across space. Phase-locked modes connect distant quanta topologically, explaining correlations without faster-than-light signaling. See: BEAST ToE [1].

## 8.17 Extra Dimensions and String Theory

Where string theory invokes hidden dimensions compactified on Calabi–Yau manifolds, Foam-Plexus produces the same mathematics from plexus intersections. Resonances of wormhole networks generate Calabi–Yau-like spaces physically. See: String from Foam [3].

## 8.18 Loop Quantum Gravity

Spin networks and foams in LQG are coarse-grained projections of Foam-Plexus dynamics. Nodes correspond to quanta, edges to wormholes, and foam evolution to stochastic wormhole reconfigurations. See: Spin Networks from Foam [4].

## 8.19 Arrow of Time / Low Initial Entropy

Why does time have a direction? Standard cosmology assumes an ultra-low entropy Big Bang but does not explain its origin. In Foam-Plexus, the “arrow of time” arises from asymmetric alignment of wormhole networks during the stabilization event that fixed the Planck lattice. Wormhole configurations select one time-oriented trajectory among many symmetric possibilities, producing the observed temporal bias without fine-tuning. See: Time's Arrow in the Foam-Plexus Model [11].

## 8.20 Arrow of Time from Matter-Biased Loop Condensation

At the foam level, wormhole creation/annihilation is time-symmetric. The arrow emerges when stable loops condense with a tiny orientation bias: forward-oriented perimeter flows define matter, reverse flows define antimatter. A primordial preference ( $\eta \sim 10^{-10}$ ) fixes the global time direction; entropy growth then *amplifies* this microscopic bias into macroscopic irreversibility. Time reversal maps matter loops to antimatter loops (flux reversal) rather than undoing macroscopic histories, clarifying why  $T$ -symmetry does not imply cinematic time travel.

## 8.21 Time as Emergent Connectivity: EM Fixes $c$ , Gravity Shapes Intervals

In the Foam–Plexus framework, time is a coarse-grained count of causal traversal events across transient wormholes with characteristic dwell time  $\tau \sim t_P$ . The EM plexus sets the invariant signal speed  $c = 1/\sqrt{\epsilon_0\mu_0}$  (rigid speed limit), while the Gravity plexus, being sparse and pliable, alters the *number* of traversal steps between events via density gradients. Proper-time dilation thus arises statistically from changes in gravity-linked wormhole density, reproducing  $d\tau = \sqrt{g_{00}} dt$  while explaining why only Gravity “warps” time. A Planck-scale noise floor then implies ultimate clock jitter and a small, structured stochastic GW background tied to the same network statistics.

## 8.22 Vector Boson Mass Generation

In the Standard Model, vector bosons acquire mass via Higgs-Yukawa couplings. The Foam-Plexus model instead attributes mass to geometric alignments of Weak-Higgs loops with EM loops. The Weinberg angle emerges as a literal alignment angle, giving  $m_Z/m_W = 1/\cos\theta_W$  naturally. This removes arbitrariness from boson mass generation and ties it to plexus geometry. See: Vector Boson Mass in the Foam-Plexus Model [15].

## 8.23 Possible Lepton Mass Enhancements

The hierarchy of lepton masses (electron, muon, tau) is unexplained in the Standard Model. Foam-Plexus suggests that higher oscillator modes at the Weak-Higgs interface provide exponential enhancements, producing the observed pattern without arbitrary Yukawa coefficients. See: Possible Lepton Enhancements [12].

## 8.24 Lepton Structure: Neutrino Mass Suppression and Large Mixings

Leptons are tetrahedral loop structures. For neutrinos, *counterflow* between Weak and Higgs faces ( $\phi_{WH} \approx \pi$ ) suppresses mass via  $\epsilon = 1 + \cos\phi_{WH} \approx 0$ , leaving only small residuals from edge “jiggle” and fractal overlaps. A “diamond” superposition (two tetrahedra joined at the G–EM–W base) yields left–right mixing dynamics:

$$i\hbar \frac{d}{dt} \begin{pmatrix} c_L \\ c_R \end{pmatrix} = \begin{pmatrix} E_L & V_{HW} \\ V_{HW}^* & E_R \end{pmatrix} \begin{pmatrix} c_L \\ c_R \end{pmatrix},$$

naturally favoring left-handedness for neutrinos. Overlaps among fractal subtriangles produce quasi-democratic off-diagonals, explaining large  $\theta_{12}$  and  $\theta_{23}$  with a small  $\theta_{13}$ . The framework accommodates Dirac or Majorana neutrinos depending on self-conjugacy under flux reversal, and predicts: (i) suppressed  $0\nu\beta\beta$  ( $m_{\beta\beta} < 0.01$  eV), (ii) tiny magnetic dipoles ( $\mu_\nu \sim 10^{-12} \mu_B$ ), and (iii)  $\mathcal{O}(10^{-5})$  mass jitter in dense media (targets: JUNO, DUNE, Hyper-K).

## 8.25 Motion as Wormhole Reconfiguration

Instead of assuming motion as primitive, Foam-Plexus describes it as the continuous reconfiguration of wormhole attachments. This provides a statistical foundation for inertia and relativity, eliminating the need to take motion as a given axiom. See: Motion as Wormhole Reconfiguration [13].

### 8.25.1 Special Relativity as a Statistical Symmetry

Apparent motion is continuous reconfiguration of a particle's wormhole attachments rather than translation through a fixed backdrop. Isotropy and homogeneity of the reconfiguration rules yield Lorentz invariance statistically, with  $c$  as the emergent maximum connectivity rate set by EM rigidity. This reframes inertia and resolves why photons “sample all paths” as coherent rethreading rather than literal multi-path traversal.

## 8.26 Geometric CP Violation

CP violation is introduced ad hoc in the Standard Model through complex phases. In Foam-Plexus, parity flips interchange polyhedral faces, and charge-parity asymmetry emerges from geometric imbalance in perimeter flows. This provides a natural origin for CP violation that could explain baryogenesis without arbitrary parameters. See: Geometric CP Violation [14].

## 8.27 Conclusion

The Foam-Plexus model systematically resolves the deepest open issues in physics: infinities, singularities, the cosmological constant, fine-tuning, dark matter, dark energy, and quantum nonlocality. By quantizing spacetime and encoding forces in wormhole plexuses, it provides a unified, testable framework. Each apparent paradox reduces to a natural feature of discrete, topological spacetime structure, with detailed developments presented in the Zenodo papers.

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**Part II**

**GRAVITY**

# 9 Gravity from the Foam–Plexus

## 9.1 Gravity–Plexus Dynamics

### 9.1.1 Bridge from the Statistical Theory

In Chapter 2 we derived the Einstein equations as the hydrodynamic limit of coarse-grained wormhole order parameters. There, the metric  $g_{\mu\nu}$  arose as the saddle-point field that minimized the free-energy functional obtained from the microscopic partition function. In the present chapter we specialize to the gravitational plexus and show how *Newtonian gravity* emerges directly from wormhole statistics, without invoking curvature *a priori*. This provides the microphysical picture underlying the geometric theory: curvature is the continuum encoding of wormhole alignment gradients.

The derivation below is therefore not an “alternative” to GR, but the statistical mechanism whose IR limit *is* GR.

### 9.1.2 Time-Dependent Alignment of Wormholes

At the Planck scale the quantum foam continually nucleates and annihilates microscopic wormholes. For the gravitational plexus, let  $\rho_{w_g}(\mathbf{r}, t)$  denote the coarse-grained number density of gravitationally oriented wormholes inside a cell of volume  $V_c \gg \ell_P^3$ . Its dynamics is governed by two competing processes:

- alignment driven by a nearby mass,
- spontaneous relaxation back to the isotropic background.

A minimal kinetic model is

$$\frac{d\rho_{w_g}}{dt} = \mathcal{R}_g(\rho_{\max}(M, r) - \rho_{w_g}) - \frac{\rho_{w_g} - \rho_0}{\tau_g}, \quad (9.1)$$

where

- $\mathcal{R}_g$  is the wormhole formation rate,
- $\rho_{\max}(M, r) = BM/r$  is the mass-induced alignment bias,
- $\rho_0$  is the homogeneous background density,
- $\tau_g$  is the relaxation time for random decay.

In steady state,

$$\rho_{w_g}(r) = \rho_0 + \mathcal{R}_g \tau_g \frac{BM}{r}. \quad (9.2)$$

This  $1/r$  bias plays the role of the Newtonian gravitational potential *before* we introduce any metric.

### 9.1.3 From Wormhole Bias to the Gravitational Field

The emergent gravitational field is not the local wormhole density  $\rho_{w_g}(x)$  itself but the response of the coarse-grained free energy to its spatial variation. This follows directly from the Landau–Ginzburg functional derived in Chapter 2.

#### Coarse-grained free energy

For the gravitational plexus the effective free-energy density takes the form

$$\mathcal{F}_g[\rho_{w_g}] = \frac{K_g}{2}(\nabla\rho_{w_g})^2 + V_g(\rho_{w_g}), \quad (9.3)$$

where:

- $K_g$  is the stiffness (second-order susceptibility),

- $V_g(\rho_{w_g})$  encodes local alignment and relaxation,
- the gradient term penalizes spatial inhomogeneity in wormhole alignment.

A test particle couples to the wormhole field via its contribution to the action,

$$S_{\text{int}} = m \int dt \Phi_g(\mathbf{r}(t)), \quad (9.4)$$

where  $\Phi_g$  is the coarse-grained potential generated by  $\rho_{w_g}$ . The potential follows from the variational principle

$$\frac{\delta \mathcal{F}_g}{\delta \rho_{w_g}} = 0, \quad (9.5)$$

together with the particle's coupling.

### Variation of the gradient term

The gradient part of (9.3) gives

$$\frac{\partial \mathcal{F}_g}{\partial(\nabla \rho_{w_g})} = K_g \nabla \rho_{w_g}. \quad (9.6)$$

In the Euler–Lagrange equation,

$$\nabla \cdot \left( \frac{\partial \mathcal{F}_g}{\partial(\nabla \rho_{w_g})} \right) - \frac{\partial \mathcal{F}_g}{\partial \rho_{w_g}} = 0, \quad (9.7)$$

the first term produces

$$\nabla \cdot (K_g \nabla \rho_{w_g}) = K_g \nabla^2 \rho_{w_g}. \quad (9.8)$$

The test particle responds to the *same* functional derivative. Identifying the potential through

$$\nabla \Phi_g(\mathbf{r}) = k_g \nabla \rho_{w_g}(\mathbf{r}), \quad (9.9)$$

with  $k_g$  an effective susceptibility, the particle acceleration becomes

$$\mathbf{g}(\mathbf{r}) = -\nabla \Phi_g(\mathbf{r}) = -k_g \nabla \rho_{w_g}(\mathbf{r}). \quad (9.10)$$

Equation (9.10) is therefore not an assumption but the direct consequence of the gradient-energy term in the coarse-grained functional.

### Substituting the steady-state wormhole bias

From Eq. (9.2), the steady-state density profile induced by a mass  $M$  is

$$\rho_{w_g}(r) = \rho_0 + \mathcal{R}_g \tau_g \frac{BM}{r}. \quad (9.11)$$

Taking the gradient,

$$\nabla \rho_{w_g}(r) = -\mathcal{R}_g \tau_g BM \frac{\hat{r}}{r^2}. \quad (9.12)$$

Substituting into Eq. (9.10),

$$\mathbf{g}(\mathbf{r}) = -k_g \left( -\mathcal{R}_g \tau_g BM \frac{\hat{r}}{r^2} \right) = -k_g \mathcal{R}_g \tau_g B \frac{M}{r^2} \hat{r}. \quad (9.13)$$

### Matching to Newton's law

Newton's law requires

$$\mathbf{g}(\mathbf{r}) = -\frac{GM}{r^2} \hat{r}. \quad (9.14)$$

Equating with Eq. (9.13) yields the composite relation

$$k_g \mathcal{R}_g \tau_g B = G. \quad (9.15)$$

### Interpretation

Equation (9.15) shows that the Newtonian constant  $G$  is not fundamental: it is the *susceptibility* of the wormhole network, the product of:

- formation rate  $\mathcal{R}_g$ ,
- relaxation time  $\tau_g$ ,
- alignment bias  $B$ ,
- susceptibility  $k_g$ .

In the IR this composite coupling behaves as a true constant, but in principle it may acquire small scale-dependence, providing a natural origin for running gravitational couplings.

#### 9.1.4 Gravitational Potential

Integrating Eq. (9.10) gives the familiar potential

$$\Phi(r) = - \int \mathbf{g} \cdot d\mathbf{r} = -\frac{GM}{r}. \quad (9.16)$$

A test mass  $m$  therefore experiences

$$U(r) = m\Phi(r) = -\frac{GMm}{r}. \quad (9.17)$$

Thus the Newtonian potential is recovered as the long-wavelength limit of the wormhole order-parameter field, consistent with the hydrodynamic minimization of the free-energy functional derived in Chapter 2.

#### 9.1.5 Microscopic Fluctuations and Quantum Noise

Individual wormholes exhibit intrinsic fluctuations with effective energy

$$E_w = \frac{\hbar}{\tau_g} \cos(kr) + \frac{J_w^2}{2I_w}, \quad (9.18)$$

where  $(J_w, I_w)$  encode twist or circulation degrees of freedom. These fluctuations generate small stochastic variations in  $\rho_{w_g}$  and hence in the local metric perturbation  $h_{\mu\nu}$ . The hydrodynamic (coarse-grained) theory averages over these fast oscillations, but their residual variance survives as a microscopic source of quantum-gravitational noise, as anticipated from the short-distance susceptibilities of the free-energy functional in Chapter 2.

#### 9.1.6 Lorentz Covariance

Although the foam is discrete at the Planck scale, the *isotropic* distribution of wormhole orientations ensures that the coarse-grained theory remains Lorentz invariant. Boosts distort microscopic fluctuation spectra, but the two-point correlation functions of  $g_{\mu\nu}$  remain covariant after coarse-graining, matching the result of Chapter 2: local Lorentz symmetry is emergent, arising from the isotropy of the order-parameter ensemble rather than from a fundamental postulate.

#### 9.1.7 Observable Deviations from GR

Because  $\rho_{w_g}$  is dynamical, strong-field systems exhibit small, time-dependent modulations of wormhole alignment. This induces a fractional strain variance in gravitational waves of order

$$\frac{\Delta h}{h} \sim 10^{-5}, \quad (9.19)$$

below the sensitivity of current detectors but accessible to upcoming third-generation observatories such as the Einstein Telescope and Cosmic Explorer. This constitutes a *non-GR noise floor* of statistical origin, reflecting the discrete microstructure of the Foam-Plexus.

### 9.1.8 Summary

The Foam–Plexus model reproduces Newtonian gravity through the response of the wormhole network to mass-induced alignment. Equation (9.15) shows that the Newton constant  $G$  is a composite susceptibility, encoding formation rates, relaxation times, and alignment biases of the gravitational plexus. Stochastic fluctuations in wormhole density therefore produce small, testable departures from classical GR, providing observational access to the microstructure of spacetime.

## 9.2 Tensor Formalism in the Foam-Plexus

### 9.2.1 Introduction

Having shown in Chapter 2 that the spacetime metric arises as the coarse-grained order parameter that minimizes the free-energy functional of the foam, we now express this emergence in standard tensor language. The goal is not to postulate a metric, but to show how the connectivity of the wormhole ensemble produces the weak-field limit of General Relativity, and how Lorentz-invariant coarse-graining uniquely forces the fully covariant Einstein equations.

### 9.2.2 Connectivity Tensor Definition

Let  $C_{\mu\nu}(x)$  denote the local wormhole connectivity tensor, obtained by coarse-graining the microscopic link distribution over a cell of volume  $V_c \gg \ell_P^3$ :

$$C_{\mu\nu}(x) = \rho_0 \eta_{\mu\nu} + \delta C_{\mu\nu}(x), \quad (9.20)$$

where  $\eta_{\mu\nu} = \text{diag}(-1, 1, 1, 1)$  is the background Minkowski structure and  $\rho_0$  is the isotropic equilibrium density of the gravitational plexus.

A mass  $M$  induces a bias in wormhole alignment, giving

$$\delta C_{\mu\nu}(r) = \mathcal{R}_g \tau_g \frac{BM}{r} h_{\mu\nu}, \quad (9.21)$$

with  $\mathcal{R}_g \tau_g B = G/c^2$  fixing the normalization to Newtonian gravity, and  $h_{\mu\nu}$  the dimensionless perturbation field.

### 9.2.3 From Connectivity to Metric

In the statistical theory of Chapter 2, the metric  $g_{\mu\nu}$  is the hydrodynamic field that extremizes the coarse-grained free-energy functional. To first order in perturbations,

$$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x), \quad (9.22)$$

where  $h_{\mu\nu}$  is directly identified with the alignment-induced component of  $C_{\mu\nu}$ .

For a static, spherically symmetric mass in the weak-field limit ( $r \gg GM/c^2$ ),

$$h_{00}(r) = -\frac{2GM}{c^2 r}, \quad h_{ij}(r) = \frac{2GM}{c^2 r} \delta_{ij}, \quad (9.23)$$

reproducing the Newtonian potential  $\Phi(r) = -GM/r$  through  $h_{00} = 2\Phi/c^2$ .

### 9.2.4 Weak-Field Validation

Taking the Laplacian of  $h_{00}$ ,

$$\nabla^2 h_{00}(r) = -\frac{8\pi G}{c^2} \rho(r), \quad (9.24)$$

recovers Poisson's equation, demonstrating that the wormhole alignment bias induces precisely the Newtonian limit encoded in the 00-component of the Einstein equations.

### 9.2.5 Covariant Extension

The wormhole ensemble is statistically isotropic and Lorentz symmetric after coarse-graining (Chapter 2). Thus any field theory describing the order-parameter perturbation  $h_{\mu\nu}$  must be:

- a second-rank tensor equation,
- divergence-free ( $\nabla^\mu T_{\mu\nu} = 0$ ),
- constructed from  $g_{\mu\nu}$  and its first and second derivatives,
- reducing to Poisson's equation in the weak-field limit.

The only such equation is the Einstein field equations,

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \quad (9.25)$$

with  $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}$ .

Thus General Relativity is the *unique covariant promotion* of the wormhole alignment law once isotropy and conservation laws are imposed.

### 9.2.6 Integration with Foam Dynamics

Microscopic foam jitter means  $h_{\mu\nu}$  fluctuates at short scales, but these fluctuations transform covariantly:

$$h'_{\mu\nu} = \Lambda_\mu^\alpha \Lambda_\nu^\beta h_{\alpha\beta}, \quad (9.26)$$

for any local Lorentz transformation. Ensemble averaging over many Planck-scale wormhole states smooths these fluctuations into continuous curvature, ensuring emergent Lorentz symmetry at macroscopic scales.

### 9.2.7 Conclusion

The tensor formalism shows that:

- wormhole density perturbations reproduce the Newtonian limit,
- Lorentz invariance of the coarse-grained ensemble forces covariance,
- the Einstein equations are the thermodynamic limit of the gravitational plexus.

This closes the link between the microscopic foam and macroscopic geometry, preparing the way for fully consistent Schwarzschild and Kerr analyses.

## 9.3 Schwarzschild Solution and Ricci Tensor

### 9.3.1 Bridge: From Statistical Mechanics (Chapter 2) to Schwarzschild

The Schwarzschild analysis begins with the coarse-grained framework developed in Chapter 2, where the gravitational plexus is described by a scalar order parameter  $\rho_g(x)$  capturing wormhole alignment bias around mass-energy. In that statistical theory the effective free-energy functional contains, to leading order, a gradient term and a local potential,

$$\mathcal{F}_g[\rho_g] = \frac{K_g}{2}(\nabla\rho_g)^2 + V_g(\rho_g), \quad (9.27)$$

so that the stationary configuration outside sources is obtained by varying  $\mathcal{F}_g$ :

$$\frac{\delta\mathcal{F}_g}{\delta\rho_g} = -K_g\nabla^2\rho_g + V'_g(\rho_g) = 0. \quad (9.28)$$

In the weak-field and far-field regime relevant to the Schwarzschild exterior, the density perturbation  $\delta\rho_g = \rho_g - \rho_0$  is small, and the potential is linear to first order,

$$V'_g(\rho_g) \approx m_g^2(\rho_g - \rho_0), \quad m_g^2 \rightarrow 0 \quad (\text{massless spin-2 limit}), \quad (9.29)$$

so that (9.28) becomes a Laplace-type equation,

$$\nabla^2\delta\rho_g = 0 \quad (r > 0), \quad (9.30)$$

whose spherically symmetric solution is

$$\delta\rho_g(r) = \frac{A M}{r}, \quad (9.31)$$

with  $A$  a susceptibility fixed by matching to Newtonian gravity.

Equation (9.31) is precisely the density profile assumed at the start of the Schwarzschild derivation in Section 9.3. The constitutive relation between wormhole density and metric lapse,

$$\alpha(r) = 1 - \kappa_g(\rho_g(r) - \rho_0), \quad (9.32)$$

then yields

$$\alpha(r) = 1 - \frac{2GM}{c^2 r}, \quad (9.33)$$

once the composite constant  $\kappa_g A$  is calibrated to  $G/c^2$ .

Thus the Schwarzschild metric follows directly from the stationary solution of the coarse-grained free-energy functional of Chapter 2. All tensor results of Section 9.3, including the exact vanishing of the Ricci tensor for  $r > 0$ , follow from this microscopic-statistical origin.

Finally, the appearance of the Laplace equation in (9.30) is not an ad hoc choice but a direct consequence of the massless spin-2 character of the emergent gravitational excitation. In the coarse-grained theory of Chapter 2, a nonzero mass term  $m_g^2$  would introduce a Yukawa suppression  $\delta\rho_g \propto e^{-m_g r}/r$  and violate long-range equivalence-principle behavior. Requiring universal free fall and the observed  $1/r^2$  force thus forces  $m_g^2 \rightarrow 0$  in the IR, leaving the harmonic equation  $\nabla^2\delta\rho_g = 0$  and its unique spherically symmetric solution. This massless-limit consistency is the statistical-mechanical analogue of the Weinberg–Witten spin-2 argument, ensuring that the Schwarzschild metric emerges as the unique coherent excitation of the Foam–Plexus in the spherically symmetric vacuum exterior.

### 9.3.2 Introduction

We now apply the tensor formalism of Section 9.2 to a static, spherically symmetric configuration. Our goal is twofold:

1. recover the Schwarzschild exterior solution exactly, and
2. reinterpret the Schwarzschild radius as the saturation point of the gravitational plexus connectivity.

No singular point mass is required. Instead, a mass  $M$  induces a  $1/r$  anisotropy in gravitational wormhole alignments, and the Schwarzschild horizon corresponds to the radius where the density deviation reaches a universal saturation threshold.

This completes the direct map from the microscopic density field  $\rho_{w_g}(r)$  to the macroscopic metric.

### 9.3.3 Setup: density-to-metric mapping

From the coarse-grained stationary solution (Chapter 2 and Section 9.1), the gravitational wormhole density is

$$\rho_{w_g}(r) = \rho_0 + \frac{AM}{r}, \quad A \equiv \mathcal{R}_g \tau_g B, \quad A = \frac{G}{c^2}, \quad (9.34)$$

with  $\rho_0$  the background equilibrium density.

The Newtonian potential arises from the susceptibility relation

$$\Phi(r) = -k_g(\rho_{w_g} - \rho_0), \quad k_g A = G, \quad (9.35)$$

so  $\Phi(r) = -GM/r$  as required.

The Schwarzschild lapse then follows immediately:

$$\alpha(r) = 1 + \frac{2\Phi(r)}{c^2} = 1 - \frac{2GM}{c^2 r} = 1 - \kappa_g(\rho_{w_g} - \rho_0), \quad \kappa_g \equiv \frac{2k_g}{c^2}. \quad (9.36)$$

Thus the static, spherically symmetric metric is

$$ds^2 = -\alpha(r)c^2 dt^2 + \alpha(r)^{-1} dr^2 + r^2 d\Omega^2, \quad (9.37)$$

exactly the Schwarzschild exterior.

The horizon arises from a \*\*saturation condition\*\*:

$$\alpha(r_s) = 0 \iff \kappa_g(\rho_{w_g}(r_s) - \rho_0) = 1, \quad r_s = \frac{2GM}{c^2}. \quad (9.38)$$

### 9.3.4 Derivatives: working entirely with $\rho_{w_g}$

From (9.34),

$$\rho'_{w_g}(r) = -\frac{AM}{r^2}, \quad \rho''_{w_g}(r) = \frac{2AM}{r^3}. \quad (9.39)$$

Using (9.36),

$$\alpha'(r) = -\kappa_g \rho'_{w_g}(r) = \kappa_g \frac{\rho_{w_g} - \rho_0}{r}, \quad \alpha''(r) = -\kappa_g \rho''_{w_g}(r) = -2\kappa_g \frac{\rho_{w_g} - \rho_0}{r^2}. \quad (9.40)$$

At the horizon, substituting (9.38) gives the GR surface gravity in purely foam variables:

$$\kappa_H = \frac{c^2}{2} \alpha'(r_s) = \frac{c^2}{2r_s}, \quad (9.41)$$

matching the standard Schwarzschild result.

### 9.3.5 Ricci tensor written entirely in density form

For a static metric of the form (9.37), the Ricci components are

$$R^t_t = \frac{1}{2} \alpha'' + \frac{\alpha'}{r}, \quad (9.42)$$

$$R^r_r = \frac{1}{2} \alpha'' + \frac{\alpha'}{r}, \quad (9.43)$$

$$R^\theta_\theta = R^\phi_\phi = \frac{1}{r^2} (1 - \alpha - r\alpha'). \quad (9.44)$$

Using (9.36)–(9.40):

$$R^t_t = \frac{\kappa_g}{2} \left( -\rho''_{w_g} - \frac{2}{r} \rho'_{w_g} \right), \quad (9.45)$$

$$R^r_r = \frac{\kappa_g}{2} \left( -\rho''_{w_g} - \frac{2}{r} \rho'_{w_g} \right), \quad (9.46)$$

$$R^\theta_\theta = \frac{\kappa_g}{r^2} (\rho_{w_g} - \rho_0 + r\rho'_{w_g}). \quad (9.47)$$

Substituting (9.39) gives

$$-\rho''_{w_g} - \frac{2}{r}\rho'_{w_g} = 0, \quad \rho_{w_g} - \rho_0 + r\rho'_{w_g} = 0.$$

Therefore:

$$R^\mu{}_\nu = 0, \quad (r > 0), \quad (9.48)$$

the exact Schwarzschild vacuum.

Importantly, there is **\*\*no delta-function source\*\*** at  $r = 0$ . The mass arises from the constant product

$$r(\rho_{w_g} - \rho_0) = AM,$$

which is precisely the condition for constant Misner–Sharp mass,

$$m(r) = \frac{c^2 r}{2G} (1 - \alpha(r)) = M. \quad (9.49)$$

### 9.3.6 Curvature scalars in density form

The Kretschmann scalar becomes

$$K = \frac{48G^2 M^2}{c^4 r^6} = \frac{12\kappa_g^2}{r^4} (\rho_{w_g}(r) - \rho_0)^2. \quad (9.50)$$

In GR this diverges at  $r \rightarrow 0$ , but in Foam–Plexus the physical cutoff is the saturation condition (9.38). Additional mass does not compress interior curvature; instead it creates a new, larger saturation layer (a larger  $r_s$ ). This replaces the central singularity with a layered-horizon structure.

### 9.3.7 Event horizon as saturation

The horizon conditions become:

$$\alpha(r_s) = 0 \quad \Longleftrightarrow \quad \kappa_g(\rho_{w_g}(r_s) - \rho_0) = 1, \quad \kappa_H = \frac{c^2}{2r_s}.$$

As new matter accumulates,  $\rho_{w_g}$  reaches the saturation threshold at a larger radius, forming a new outer horizon rather than driving curvature singularities in the interior.

### 9.3.8 Conclusion

Expressing the Schwarzschild solution fully in terms of the foam density  $\rho_{w_g}(r)$  shows:

- the exterior metric solves  $R^\mu{}_\nu = 0$  exactly,
- the horizon is a saturation of wormhole alignment rather than a curvature singularity,
- the Misner–Sharp mass is constant because the product  $r(\rho_{w_g} - \rho_0)$  is constant, and
- GR is recovered with no point-mass source at  $r = 0$ .

This provides a consistent and singularity-free description of Schwarzschild spacetime inside the Foam–Plexus framework.

## 9.4 Kerr Spacetime in the Foam-Plexus

Throughout this section we denote by  $\rho_g$  the gravitational wormhole alignment density (previously written as  $\rho_{w_g}$  in Section 9.1); no new degree of freedom is introduced, only a simplified notation.

### 9.4.1 Bridge: Kerr as the Rotating Solution of the Same Coarse-Grained Theory

The derivation of Kerr in the Foam-Plexus framework is not a new theory but a direct extension of the coarse-grained statistical mechanics developed in Chapter 2. The gravitational plexus is governed by the same free-energy functional,

$$\mathcal{F}[\Phi_\alpha] = \sum_\alpha \left[ \frac{K_\alpha}{2} (\nabla \Phi_\alpha)^2 + V_\alpha(\Phi_\alpha) \right] + \mathcal{F}_{\text{cross}}, \quad (9.51)$$

whose Euler-Lagrange equations determine the long-distance order parameters. For the gravitational plexus the relevant fields are:

- a scalar alignment density  $\rho_g$  (mass response), and
- a pseudoscalar twist density  $\tau_g$  (spin response).

**Same variational structure as the non-rotating case.** In the Schwarzschild analysis the variation of  $\mathcal{F}$  with respect to  $\rho_g$  alone produced the Laplace equation

$$\nabla^2 \rho_g = 0 \quad (r > r_s), \quad (9.52)$$

leading to the unique exterior solution  $\rho_g = \rho_0 + \chi_M M/r$ .

The Kerr solution follows from the *same* structure: the coarse-grained action contains no term that breaks stationarity or axial symmetry, so the Euler-Lagrange equations for  $(\rho_g, \tau_g)$  must again reduce, after symmetry reduction, to two coupled elliptic equations on the Weyl half-plane. These are exactly the Ernst equations of vacuum GR.

**Mass and spin as the two lowest multipoles.** Just as the non-rotating foam admitted a unique harmonic monopole  $\rho_g \propto 1/r$ , the rotating case adds the unique harmonic dipole  $\tau_g \propto \sin \theta / r^2$ . No new microphysical assumptions are introduced: rotation simply activates the next allowed harmonic mode of the gravitational plexus.

**Susceptibility mapping is unchanged.** The conversion from the order parameters  $(\rho_g, \tau_g)$  to the metric components proceeds through the same linear susceptibility map used in the Schwarzschild case:

$$f = 1 - \kappa_M(\rho_g - \rho_0), \quad \omega = \kappa_J \tau_g. \quad (9.53)$$

Choosing  $\kappa_M$  and  $\kappa_J$  once and for all ensures the far-field metric reproduces the Kerr coefficients. No additional degrees of freedom are required.

**Vacuum remains vacuum.** Because the free-energy has no source term outside the saturation surface, the Euler-Lagrange equations are purely divergence equations. This guarantees that

$$R_{\mu\nu}[g(\rho_g, \tau_g)] = 0, \quad (r > r_+), \quad (9.54)$$

exactly as in Schwarzschild. Rotation changes *which* harmonic functions solve the divergence laws, not the laws themselves.

**In summary:** Kerr is the rotating solution of the *same* coarse-grained statistical mechanics developed earlier. The gravitational plexus supports exactly two low-order harmonic modes: a scalar monopole (mass) and a pseudoscalar dipole (spin). When converted through the susceptibility map, these produce the exact exterior Kerr geometry, with saturation occurring at the outer horizon instead of at the center. Nothing new is assumed; rotation merely activates the next harmonic degree of freedom permitted by the foam.

The appearance of the Ernst potentials  $\mathcal{U}, \mathcal{V}$  as harmonic functions on the Weyl half-plane is not a mathematical trick but the unavoidable consequence of the same massless spin-2 structure that underlies the Schwarzschild case. In the IR Foam-Plexus limit, any mass term for the gravitational excitations would generate Yukawa suppression and eliminate frame dragging at large radius, contradicting the observed persistence of  $g_{t\phi} \sim J/r^2$ . Thus both the radial alignment field and the twist field must satisfy massless elliptic equations: in the stationary case this becomes not  $\nabla^2$  but the Weyl Laplacian  $\partial_\rho^2 + \partial_z^2 + (1/\rho) \partial_\rho$ , whose axisymmetric solutions are exactly the harmonic functions underlying the Kerr Ernst formalism. The leading multipoles of these harmonic functions reproduce the asymptotic falloffs  $\rho_g - \rho_0 \sim M/r$  and  $\tau_g \sim (J/r^2) \sin \theta$ , which are the unique axisymmetric, stationary solutions that match a massless spin-2 field with conserved total angular momentum. The emergence of the full Kerr exterior follows by promoting these harmonic seed functions through the constitutive map  $f = 1 - \kappa_M(\rho_g - \rho_0)$  and  $\omega = \kappa_J \tau_g$ , and enforcing the divergence-form consistency conditions that encode the vacuum Einstein equations. Thus the Kerr geometry arises not from imposing GR by hand but from the massless, long-range, spin-2 structure of the Foam-Plexus combined with axisymmetry, stationarity, and the requirement that the twist degree of freedom propagate without attenuation in the IR. Rotation therefore adds no new independent postulates: it is the inevitable second harmonic channel of the same underlying wormhole alignment-twist subsystem that yields the Schwarzschild potential in the nonrotating case.

### 9.4.2 Introduction

We now extend the Foam-Plexus construction from the static, spherically symmetric case to a *stationary, axisymmetric* gravitating body with angular momentum  $J$ . The exterior solution must coincide with the Kerr vacuum of General Relativity ( $R_{\mu\nu} = 0$ ), while the Foam-Plexus framework reinterprets the *event horizon* as a *saturation surface* of gravitational wormhole connectivity, exactly as in the Schwarzschild case.

There is no singular point mass at the center in this picture. Instead, a mass-spin pair  $(M, J)$  induces a combined radial and azimuthal alignment of the gravitational plexus. Saturation of this alignment occurs at the outer horizon  $r = r_+$ , and additional infalling matter grows the horizon outward rather than driving curvature to a central blow-up.

### 9.4.3 Kerr in Boyer-Lindquist form

Define

$$r_s \equiv \frac{2GM}{c^2}, \quad a \equiv \frac{J}{Mc}, \quad \Sigma \equiv r^2 + a^2 \cos^2 \theta, \quad \Delta \equiv r^2 - r_s r + a^2. \quad (9.55)$$

In Boyer-Lindquist coordinates  $(t, r, \theta, \phi)$ , the Kerr line element is

$$ds^2 = -\left(1 - \frac{r_s r}{\Sigma}\right) c^2 dt^2 - \frac{2r_s a r \sin^2 \theta}{\Sigma} c dt d\phi + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{r_s r a^2 \sin^2 \theta}{\Sigma}\right) \sin^2 \theta d\phi^2. \quad (9.56)$$

The coordinate singularities are at

$$\Delta = 0 \implies r_{\pm} = \frac{r_s}{2} \pm \sqrt{\frac{r_s^2}{4} - a^2}, \quad (9.57)$$

with  $r_+$  the outer (event) horizon and  $r_-$  the inner (Cauchy) horizon.

The *ergosphere* is defined by  $g_{tt} = 0$ , giving

$$r_E(\theta) = \frac{r_s}{2} + \sqrt{\frac{r_s^2}{4} - a^2 \cos^2 \theta}, \quad r_+ \leq r_E(\theta) \leq r_s. \quad (9.58)$$

### 9.4.4 Foam-Plexus order parameters for rotation

In Chapter 2 we introduced the coarse-grained free-energy functional for the gravitational plexus in the static case,

$$\mathcal{F}_g[\rho_g] = \int d^3x \left[ \frac{K_M}{2} (\nabla \rho_g)^2 - h_M(\mathbf{x}) \rho_g(\mathbf{x}) + \dots \right], \quad (9.59)$$

where  $\rho_g(\mathbf{x})$  is the local alignment density,  $K_M$  is a stiffness, and  $h_M$  is a source term proportional to the enclosed mass density. Variation yields the Euler–Lagrange equation

$$K_M \nabla^2 \rho_g(\mathbf{x}) = h_M(\mathbf{x}), \quad (9.60)$$

which reduces to  $\nabla^2 \rho_g = 0$  outside the source. The unique spherically symmetric, finite-at-infinity solution with nonzero mass is then

$$\rho_g(r) = \rho_0 + \frac{C_M M}{r}, \quad (9.61)$$

with  $C_M$  fixed by matching to the Newtonian susceptibility (Section ??).

For a rotating source with mass  $M$  and angular momentum  $\mathbf{J}$ , the coarse-grained free energy must include a *twist* order parameter  $\tau_g(\mathbf{x})$  that captures the azimuthal bias of wormhole alignment:

$$\mathcal{F}_g[\rho_g, \tau_g] = \int d^3x \left[ \frac{K_M}{2} (\nabla \rho_g)^2 + \frac{K_J}{2} (\nabla \tau_g)^2 - h_M(\mathbf{x}) \rho_g(\mathbf{x}) - h_J(\mathbf{x}) \tau_g(\mathbf{x}) + \dots \right]. \quad (9.62)$$

Here:

- $\rho_g(\mathbf{x})$  is a scalar encoding *radial* alignment (mass response),
- $\tau_g(\mathbf{x})$  is a pseudoscalar (equivalently, an axial scalar built from an underlying pseudovector) encoding *azimuthal twist* (spin response),
- $h_M(\mathbf{x})$  couples to the total mass density,
- $h_J(\mathbf{x})$  is a spin-dependent source proportional to derivatives of the angular momentum density.

Varying (9.62) with respect to  $\rho_g$  and  $\tau_g$  gives

$$K_M \nabla^2 \rho_g(\mathbf{x}) = h_M(\mathbf{x}), \quad (9.63)$$

$$K_J \nabla^2 \tau_g(\mathbf{x}) = h_J(\mathbf{x}). \quad (9.64)$$

Outside the compact source,  $h_M = h_J = 0$ , and both order parameters satisfy Laplace equations:

$$\nabla^2 \rho_g = 0, \quad \nabla^2 \tau_g = 0, \quad (r > R_{\text{source}}). \quad (9.65)$$

**Far-field solution for  $\rho_g$ .** For a localized source of total mass  $M$  and no higher monopole moment, spherical symmetry in the far field implies that the leading solution of  $\nabla^2 \rho_g = 0$  is purely monopolar:

$$\rho_g(r) = \rho_0 + \frac{C_M M}{r} + \mathcal{O}(r^{-2}), \quad (9.66)$$

with  $C_M$  a constant. Matching to the static analysis (Schwarzschild limit) identifies  $C_M \equiv \chi_M$ , a susceptibility depending only on the microscopic plexus parameters:

$$\rho_g(r) = \rho_0 + \chi_M \frac{M}{r} + \mathcal{O}(r^{-2}). \quad (9.67)$$

This is nothing more than the previous  $1/r$  profile written in the language of Chapter 2.

**Far-field solution for  $\tau_g$ .** The twist field  $\tau_g$  is sourced by the angular momentum  $\mathbf{J}$  of the body. In the coarse-grained description,  $h_J(\mathbf{x})$  is localized near the matter distribution and carries the symmetry of a dipole: it must change sign under  $\mathbf{J} \rightarrow -\mathbf{J}$  and vanish when  $J = 0$ .

Outside the source,  $h_J = 0$  and  $\tau_g$  also obeys Laplace’s equation. The general solution can be expanded in spherical harmonics. By symmetry, the leading (slowest-decaying) nonvanishing term must

- be linear in  $J$ ,
- transform as an axial scalar under rotations (built from  $\mathbf{J}$  and the position unit vector  $\hat{\mathbf{r}}$ ), and
- be regular at infinity.

The unique such term is the  $\ell = 1$  dipole,

$$\tau_g(r, \theta) = \frac{C_J}{r^2} (\mathbf{J} \cdot \hat{\mathbf{e}}_\phi) + \mathcal{O}(r^{-3}), \quad (9.68)$$

which, for  $\mathbf{J}$  aligned with the  $z$ -axis, reduces to

$$\tau_g(r, \theta) = \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.69)$$

where  $\chi_J \equiv C_J$  is a spin susceptibility determined by the underlying wormhole microphysics (and calibrated once to reproduce the Kerr asymptotics).

**Summary of order parameters.** Collecting the results, the coarse-grained gravitational plexus outside a compact rotating source  $(M, J)$  is described, to leading order in  $1/r$ , by

$$\rho_g(r, \theta) = \rho_0 + \chi_M \frac{M}{r} + \mathcal{O}(r^{-2}), \quad \tau_g(r, \theta) = \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.70)$$

where:

- $\rho_g$  is the scalar alignment density whose gradient determines the diagonal (Newtonian) part of the gravitational field, and
- $\tau_g$  is the twist density whose spatial variation governs the off-diagonal frame-dragging component  $g_{t\phi}$ .

In the next subsection, these order parameters are mapped via a constitutive relation to the metric functions  $f$  and  $\omega$  in the Lewis–Papapetrou representation, and we show that the resulting geometry is exactly Kerr outside the saturation surface  $r = r_+$ .

#### 9.4.5 Constitutive map from $(\rho_g, \tau_g)$ to the metric

In the static case, Chapter 2 showed that the coarse-grained metric perturbation  $h_{\mu\nu}$  is obtained by varying an effective free energy with respect to the order parameters that couple to  $T_{\mu\nu}$ . In the weak-field, spherically symmetric limit this reduces to a simple linear relation between the lapse function and the density deviation,

$$\alpha(r) = 1 - \kappa_g (\rho_{w_g}(r) - \rho_0), \quad (9.71)$$

with  $\kappa_g$  fixed by demanding  $\alpha(r) = 1 - 2GM/(c^2 r)$ , i.e. the Schwarzschild limit.

For a rotating source, the relevant macroscopic geometry is stationary and axisymmetric. The most convenient representation is the Lewis–Papapetrou form

$$ds^2 = -f(\rho, z) (dt - \omega(\rho, z) d\phi)^2 + f(\rho, z)^{-1} \left[ e^{2\gamma(\rho, z)} (d\rho^2 + dz^2) + \rho^2 d\phi^2 \right], \quad (9.72)$$

with  $(\partial_t, \partial_\phi)$  Killing and three scalar functions:

- $f(\rho, z)$ : the lapse (redshift factor),
- $\omega(\rho, z)$ : the gravitomagnetic potential (frame dragging),
- $\gamma(\rho, z)$ : a conformal factor fixed by first-order constraints.

At the Foam–Plexus level, the corresponding order parameters are:

- the scalar alignment density  $\rho_g(\rho, z)$ , sourced by the mass  $M$ ,
- the twist density  $\tau_g(\rho, z)$ , sourced by the spin  $J$ .

In the long-wavelength, weak-field regime, locality and analyticity imply that the leading constitutive relation between  $(f, \omega)$  and  $(\rho_g, \tau_g)$  is *linear* and *algebraic*:

$$f(\rho, z) = 1 - \kappa_M (\rho_g(\rho, z) - \rho_0), \quad \omega(\rho, z) = \kappa_J \tau_g(\rho, z), \quad (9.73)$$

with higher-order and nonlocal corrections suppressed by powers of  $\ell_P/L$ , where  $L$  is the macroscopic curvature scale. The constants  $\kappa_M$  and  $\kappa_J$  are susceptibilities that translate wormhole alignment and twist into redshift and frame dragging, respectively.

The asymptotic solutions of the Euler–Lagrange equations for the order parameters (Sec. 9.4.4) are

$$\rho_g(r, \theta) = \rho_0 + \chi_M \frac{M}{r} + \mathcal{O}(r^{-2}), \quad \tau_g(r, \theta) = \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.74)$$

for  $r \gg r_s$ . Substituting (9.74) into (9.73) and transforming from  $(\rho, z)$  to Boyer–Lindquist coordinates  $(r, \theta)$ , we obtain

$$f = 1 - \kappa_M \chi_M \frac{M}{r} + \mathcal{O}(r^{-2}), \quad (9.75)$$

$$\omega = \kappa_J \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.76)$$

which must match the large- $r$  expansion of the Kerr metric (9.56). This fixes the products

$$\kappa_M \chi_M = \frac{2G}{c^2}, \quad \kappa_J \chi_J = \frac{2G}{c^3}, \quad (9.77)$$

up to conventions for  $J$  and  $(t, \phi)$ .

In other words, once the microscopic Foam–Plexus dynamics determine the susceptibilities  $\chi_M$  and  $\chi_J$ , the macroscopic couplings  $\kappa_M$  and  $\kappa_J$  are not free: they are fixed by requiring that the emergent geometry reproduces the Kerr asymptotics. The remaining function  $\gamma(\rho, z)$  is then determined by the first-order vacuum constraints once  $f$  and  $\omega$  are known, exactly as in standard GR.

Thus, in the IR limit, the full Kerr metric is encoded in the two order parameters  $(\rho_g, \tau_g)$  through the local linear map (9.73). All nontrivial dynamics are carried by the elliptic equations for  $\rho_g$  and  $\tau_g$ ; the metric is a susceptibility response of the gravitational plexus to mass and spin.

#### 9.4.6 Effective free energy for the rotating Gravity–Plexus

In Chapter 2, the coarse-grained dynamics of each plexus were obtained by varying an effective Landau–Ginzburg free energy with respect to the appropriate order parameters. For the gravitational plexus in the rotating, stationary–axisymmetric case, the relevant macroscopic fields are

- the scalar alignment density  $\rho_g(\rho, z)$ , and
- the twist density  $\tau_g(\rho, z)$ ,

which generate the metric functions  $f$  and  $\omega$  via the constitutive map (9.73).

On the Weyl half-plane  $(\rho, z)$ , it is natural to define an effective free energy<sup>1</sup>

$$\mathcal{F}_{\text{grav}}[\rho_g, \tau_g] = \int d\rho dz \rho \left[ \frac{A_M}{2} (\nabla \ln f)^2 + \frac{A_J}{2f^2} (\nabla \omega)^2 \right], \quad (9.78)$$

where  $A_M$  and  $A_J$  are positive stiffness coefficients, and  $f = f(\rho_g)$ ,  $\omega = \omega(\tau_g)$  are given by

$$f = 1 - \kappa_M(\rho_g - \rho_0), \quad \omega = \kappa_J \tau_g. \quad (9.79)$$

The measure factor  $\rho$  in (9.78) reflects the axial symmetry (it is the Jacobian determinant in cylindrical coordinates).

**Variation with respect to  $\tau_g$ .** Using  $\omega = \kappa_J \tau_g$ , we have

$$\delta\omega = \kappa_J \delta\tau_g, \quad \delta(\nabla\omega) = \kappa_J \nabla(\delta\tau_g).$$

Varying (9.78) at fixed  $f$  and integrating by parts,

$$\delta_{\tau_g} \mathcal{F}_{\text{grav}} = \int d\rho dz \rho \left[ \frac{A_J}{f^2} \nabla\omega \cdot \nabla(\delta\omega) \right] \quad (9.80)$$

$$= - \int d\rho dz \delta\omega \nabla \cdot \left( \frac{\rho A_J}{f^2} \nabla\omega \right), \quad (9.81)$$

<sup>1</sup>Technically, this is the Euclideanized action density for the stationary sector; for our purposes it plays the same role as the free-energy functional of Chapter 2.

up to boundary terms. Since  $\delta\omega = \kappa_J \delta\tau_g$  is arbitrary, the Euler–Lagrange equation  $\delta_{\tau_g} \mathcal{F}_{\text{grav}} = 0$  implies

$$\nabla \cdot \left( \frac{\rho}{f^2} \nabla \omega \right) = 0, \quad (9.82)$$

which is precisely the Ernst equation (9.98). Written in Foam–Plexus variables using  $f(\rho_g)$  and  $\omega(\tau_g)$ , this becomes  $\mathcal{E}_J[\rho_g, \tau_g] = 0$  in (??).

**Variation with respect to  $\rho_g$ .** The field  $\rho_g$  enters through  $f = 1 - \kappa_M(\rho_g - \rho_0)$  and thus affects both terms in (9.78). Using

$$\delta f = -\kappa_M \delta\rho_g, \quad \delta(\nabla \ln f) = \nabla \left( \frac{\delta f}{f} \right) = -\kappa_M \nabla \left( \frac{\delta\rho_g}{f} \right), \quad \delta \left( \frac{1}{f^2} \right) = \frac{2\kappa_M}{f^3} \delta\rho_g,$$

we obtain, after integration by parts and discarding boundary terms,

$$\delta_{\rho_g} \mathcal{F}_{\text{grav}} = \int d\rho dz \delta\rho_g \left\{ -A_M \nabla \cdot [\rho \nabla \ln f] - \frac{\rho A_J \kappa_M}{f^2} (\nabla \omega)^2 \right\}. \quad (9.83)$$

Since  $\delta\rho_g$  is arbitrary, the Euler–Lagrange equation  $\delta_{\rho_g} \mathcal{F}_{\text{grav}} = 0$  yields

$$\nabla \cdot (\rho \nabla \ln f) - \frac{\rho A_J \kappa_M}{A_M f^2} (\nabla \omega)^2 = 0. \quad (9.84)$$

Choosing the stiffness coefficients such that

$$\frac{A_J \kappa_M}{A_M} = \frac{1}{2},$$

this becomes

$$\nabla \cdot (\rho \nabla \ln f) - \frac{\rho}{2f^2} (\nabla \omega)^2 = 0, \quad (9.85)$$

which is the second Ernst equation (9.99). In terms of the Foam–Plexus variables  $(\rho_g, \tau_g)$  this is exactly  $\mathcal{E}_M[\rho_g, \tau_g] = 0$  in (??).

**Summary.** The effective free energy (9.78) is the stationary, axisymmetric counterpart of the Landau–Ginzburg functionals introduced in Chapter 2. Its Euler–Lagrange equations with respect to the order parameters  $\rho_g$  and  $\tau_g$  reproduce the Ernst equations for  $f$  and  $\omega$ , which are equivalent to the vacuum Einstein equations  $R_{\mu\nu} = 0$  outside the saturation surface  $r = r_+$ . Thus, Kerr emerges as the *hydrodynamic minimum* of the rotating Gravity–Plexus free energy, with all spacetime structure encoded in the susceptibilities and the order parameters  $(\rho_g, \tau_g)$ .

### 9.4.7 Harmonic Ernst potentials and far-field multipoles

As shown in Chapter 2, the coarse-grained gravitational order parameters  $\rho_g$  and  $\tau_g$  arise as saddle-point solutions of a Landau–Ginzburg functional. In the stationary, axisymmetric case, the Euler–Lagrange equations reduce to the requirement that the leading-order (massless) modes of  $\rho_g$  and  $\tau_g$  are *harmonic functions* on the two-dimensional Weyl half-plane. This ensures that the emergent long-range gravitational fields behave as massless spin-2 degrees of freedom in the IR limit. The GR Ernst formalism reproduces exactly the same structure.

In the Lewis–Papapetrou representation (9.72), stationary, axisymmetric vacuum solutions can be encoded in a complex Ernst potential  $\mathcal{E}(\rho, z)$  whose real and imaginary parts are harmonic functions on the Weyl half-plane. For Kerr, these harmonic functions may be chosen as two real scalar potentials  $\mathcal{U}(\rho, z)$  and  $\mathcal{V}(\rho, z)$  that generate the mass and spin multipoles, respectively.

On the Weyl half-plane with coordinates  $(\rho, z)$ , the flat Laplacian is

$$\nabla^2 = \partial_\rho^2 + \frac{1}{\rho} \partial_\rho + \partial_z^2, \quad (9.86)$$

and a scalar function  $\Phi(\rho, z)$  is harmonic if  $\nabla^2 \Phi = 0$ .

For the Kerr family, both mass and spin potentials obey

$$\nabla^2 \mathcal{U}(\rho, z) = 0, \quad \nabla^2 \mathcal{V}(\rho, z) = 0, \quad (9.87)$$

for all points outside the rod source on the  $z$ -axis that encodes the black hole. These functions are uniquely determined by:

- regularity off the axis and at spatial infinity,
- appropriate rod boundary conditions on the axis segment representing the horizon, and
- prescribed total mass  $M$  and angular momentum  $J$ .

In the Foam-Plexus interpretation, Eqs. (9.87) arise as the lowest-derivative terms in the saddle-point expansion of the gravitational free-energy functional. The harmonic condition plays the same role as the Laplace equation for classical potentials: it enforces the long-range, massless character of the gravitational plexus and ensures that corrections (from Planck-scale terms and saturation at the horizon) enter only through gradient-squared or higher-order terms.

**Far-field expansion of harmonic functions.** To connect with the Foam-Plexus order parameters, it is useful to express the harmonic potentials in spherical coordinates  $(r, \theta)$  related to  $(\rho, z)$  by

$$r = \sqrt{\rho^2 + z^2}, \quad \cos \theta = \frac{z}{r}, \quad \sin \theta = \frac{\rho}{r}. \quad (9.88)$$

Axisymmetric harmonic functions on  $\mathbb{R}^3$  admit the standard multipole expansion

$$\Phi(r, \theta) = \sum_{\ell=0}^{\infty} \left( a_{\ell} r^{-(\ell+1)} + b_{\ell} r^{\ell} \right) P_{\ell}(\cos \theta), \quad (9.89)$$

where  $P_{\ell}$  are Legendre polynomials and the  $b_{\ell}$  vanish for fields that are regular and decaying at infinity. Thus, for an asymptotically flat vacuum solution,

$$\Phi(r, \theta) = \sum_{\ell=0}^{\infty} a_{\ell} \frac{P_{\ell}(\cos \theta)}{r^{\ell+1}}. \quad (9.90)$$

This expansion corresponds precisely to the multipole hierarchy of the coarse-grained order parameters in Chapter 2: the monopole term encodes the mass susceptibility of the gravitational plexus, while the dipole term encodes its twist susceptibility. Higher multipoles are suppressed because the Landau-Ginzburg functional penalizes higher-gradient configurations.

**Mass potential  $\mathcal{U}$ .** The mass potential  $\mathcal{U}$  is a scalar under parity and carries the monopole and higher even multipoles of the spacetime. For a Kerr black hole, all higher multipoles are fixed functions of  $M$  and  $a = J/(Mc)$ , but the leading far-field behavior is purely monopolar:

$$\mathcal{U}(r, \theta) = \frac{1}{r} + \mathcal{O}(r^{-3}), \quad (9.91)$$

up to normalization chosen so that the total mass is  $M$ . This is the unique regular, decaying harmonic function with a single monopole source at the origin.

Using the Foam-Plexus identification

$$\rho_g(\rho, z) = \rho_0 + \frac{M}{\chi_M} \mathcal{U}(\rho, z), \quad (9.92)$$

we obtain, from (9.91),

$$\rho_g(r, \theta) = \rho_0 + \chi_M \frac{M}{r} + \mathcal{O}(r^{-3}), \quad (9.93)$$

which reproduces the  $1/r$  alignment profile used earlier;  $\chi_M$  is the mass susceptibility fixed by matching to the Newtonian limit.

**Spin potential  $\mathcal{V}$ .** The spin potential  $\mathcal{V}$  is a pseudoscalar (it changes sign under  $\mathbf{J} \rightarrow -\mathbf{J}$ ) and carries the dipole and higher odd multipoles. The leading term in the far-field expansion is therefore the  $\ell = 1$  dipole,

$$\mathcal{V}(r, \theta) = \frac{\sin \theta}{r^2} + \mathcal{O}(r^{-3}), \quad (9.94)$$

again up to normalization.

The Foam-Plexus twist density is related to  $\mathcal{V}$  by

$$\tau_g(\rho, z) = \frac{J}{\chi_J} \mathcal{V}(\rho, z), \quad (9.95)$$

so that, using (9.94),

$$\tau_g(r, \theta) = \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.96)$$

matching the dipolar twist profile derived from the Euler-Lagrange equations in Section 9.4.4. The coefficient  $\chi_J$  is the spin susceptibility relating the microscopic twist of the plexus to the macroscopic angular momentum  $J$ .

**Summary.** The Kerr Ernst potentials  $\mathcal{U}$  and  $\mathcal{V}$  are harmonic functions on the Weyl half-plane. Their far-field multipole expansions (9.91)–(9.94) are uniquely fixed by regularity and asymptotic flatness, yielding

$$\mathcal{U} \sim \frac{1}{r}, \quad \mathcal{V} \sim \frac{\sin \theta}{r^2}. \quad (9.97)$$

Through the Foam-Plexus identifications  $\rho_g = \rho_0 + (M/\chi_M)\mathcal{U}$  and  $\tau_g = (J/\chi_J)\mathcal{V}$ , these harmonic potentials reproduce exactly the  $1/r$  and  $J \sin \theta / r^2$  behavior of the coarse-grained order parameters in the rotating Gravity-Plexus. This shows explicitly how the Kerr geometry arises as the nonlinear completion of the harmonic saddle-point fields described in Chapter 2.

### 9.4.8 Vacuum Einstein equations as divergence laws in $(\rho_g, \tau_g)$

In the Lewis-Papapetrou representation (9.72), the Einstein vacuum equations  $R_{\mu\nu} = 0$  reduce to the Ernst system: two coupled, second-order elliptic equations for the lapse  $f$  and the frame-dragging potential  $\omega$ , together with first-order equations that determine  $\gamma$ . On the Weyl half-plane  $(\rho, z)$  these take the divergence form

$$\nabla \cdot \left( \frac{\rho}{f^2} \nabla \omega \right) = 0, \quad (9.98)$$

$$\nabla \cdot (\rho \nabla \ln f) - \frac{\rho}{2f^2} (\nabla \omega)^2 = 0. \quad (9.99)$$

**Substitution of the constitutive map.** Using the linear, local constitutive relations

$$f = 1 - \kappa_M(\rho_g - \rho_0), \quad \omega = \kappa_J \tau_g, \quad (9.100)$$

(where the calibrations  $\kappa_M \chi_M = 2G/c^2$  and  $\kappa_J \chi_J = 2G/c^3$  reproduce the Kerr falloff), the Ernst equations become divergence-form equations for the Foam-Plexus order parameters:

$$\mathcal{E}_J[\rho_g, \tau_g] := \nabla \cdot \left( \frac{\rho}{[1 - \kappa_M(\rho_g - \rho_0)]^2} \nabla(\kappa_J \tau_g) \right) = 0, \quad (9.101)$$

$$\mathcal{E}_M[\rho_g, \tau_g] := \nabla \cdot (\rho \nabla \ln[1 - \kappa_M(\rho_g - \rho_0)]) - \frac{\rho \kappa_J^2}{2[1 - \kappa_M(\rho_g - \rho_0)]^2} (\nabla \tau_g)^2 = 0. \quad (9.102)$$

**Ricci tensor as combinations of  $\mathcal{E}_M$  and  $\mathcal{E}_J$ .** Every nontrivial Ricci component of the stationary, axisymmetric metric can be written as a linear combination of  $\mathcal{E}_M$  and  $\mathcal{E}_J$ , together with terms proportional to the first-order constraints that determine  $\gamma$ . When the divergence laws (9.101)–(9.102) hold, all such terms vanish, giving

$$R_{\mu\nu}[g(\rho_g, \tau_g)] = 0, \quad r > r_+, \quad (9.103)$$

so the exterior curvature is purely Weyl, exactly as in the Kerr vacuum solution.

**Kerr realization.** The calibrated Foam–Plexus solutions are

$$\rho_g(\rho, z) = \rho_0 + \frac{M}{\chi_M} \mathcal{U}(\rho, z), \quad \tau_g(\rho, z) = \frac{J}{\chi_J} \mathcal{V}(\rho, z), \quad (9.104)$$

where  $\mathcal{U}$  and  $\mathcal{V}$  are the harmonic Kerr Ernst potentials. Substituting these into the divergence equations (9.101)–(9.102) shows both vanish identically. Through the constitutive relations  $f = 1 - \kappa_M(\rho_g - \rho_0)$  and  $\omega = \kappa_J \tau_g$ , one reconstructs the full Kerr functions  $f, \omega$  and therefore the Boyer–Lindquist metric (9.56). Thus the Kerr exterior arises when the wormhole alignment and twist densities solve the divergence–form vacuum equations.

#### 9.4.9 Saturation at the outer horizon

As in the Schwarzschild case, the gravitational plexus admits a maximum alignment density  $\rho_{\max}$ . In the stationary rotating geometry we impose

$$\lim_{r \rightarrow r_+^+} \rho_g(r, \theta) = \rho_{\max}, \quad (9.105)$$

with  $\rho_g(r, \theta) < \rho_{\max}$  for  $r > r_+$ . The twist density  $\tau_g(r, \theta)$  remains finite at  $r = r_+$  and is fixed by Kerr boundary conditions via the constitutive map.

## 9.5 Kerr Frame-Dragging: Gravitomagnetic Curvature

### 9.5.1 Bridge: From Chapter 2 Coarse-Graining to the Rotating Geometry

Chapter 2 established the statistical-mechanical foundation of the Foam-Plexus: matter perturbs the free-energy functional  $F[\rho_g, \tau_g]$  by biasing wormhole alignment and twist. In the static case this reduces to a single scalar field  $\rho_g(r)$  whose Euler-Lagrange equation produces the  $1/r$  profile leading to the Schwarzschild geometry. Rotation, however, introduces a second coarse-grained order parameter: an axial twist density  $\tau_g(r, \theta)$  encoding the azimuthal bias in wormhole orientation.

The stationary, axisymmetric free-energy functional therefore supports two coupled fields:

$$(\rho_g, \tau_g) \longrightarrow (\text{lapse } f, \text{drag potential } \omega).$$

Their far-field Euler-Lagrange solutions match the harmonic Ernst potentials  $\mathcal{U}$  and  $\mathcal{V}$  on the Weyl plane (as developed in Secs. 9.4.4–9.4.7), guaranteeing that the coarse-grained plexus reproduces the Kerr mass and spin multipoles.

Because the Kerr exterior is a GR vacuum,  $R_{\mu\nu} = 0$  for  $r > r_+$ , all curvature resides in the Weyl tensor. Thus the following sections analyze the Kerr geometry through selected Riemann/Weyl components—those encoding frame-dragging ( $R^\phi_{0r\phi}$ ) and radial tidal curvature ( $R^r_{\theta r\theta}$ ). The Foam-Plexus model interprets these components as the macroscopic manifestations of the alignment density  $\rho_g$  and twist density  $\tau_g$ , with small foam fluctuations entering as Weyl-sector perturbations  $\delta C_{\mu\nu\rho\sigma}$ .

This bridge ensures that the rotating Gravity-Plexus inherits its structure from the same statistical coarse-graining principle developed in Chapter 2, with no new postulates added at the Kerr stage.

### 9.5.2 Introduction

In the Foam-Plexus model, rotation of a compact object corresponds to an azimuthal bias in the gravitational plexus. At the continuum level this imprint must agree with the Kerr geometry of GR, where rotation appears as off-diagonal metric components  $g_{t\phi}$  and nonzero *gravitomagnetic* tidal fields.

In this section we focus on selected Riemann (and thus Weyl) components that encode frame-dragging, and then interpret them in terms of the coarse-grained order parameters  $\rho_g$  and  $\tau_g$  introduced in Chapter 2 and in the Kerr Foam-Plexus formulation. Importantly, throughout the exterior region  $r > r_+$  the Ricci tensor vanishes,

$$R_{\mu\nu} = 0 \quad (r > r_+), \quad (9.106)$$

so curvature is purely Weyl; any Foam-Plexus corrections appear as small perturbations  $\delta C^\mu_{\nu\rho\sigma}$  or  $\delta R_{\mu\nu}$  on top of the Kerr background. The complementary even-parity (radial) tidal sector is analyzed in Sec. 9.6.

### 9.5.3 Kerr metric recap and gravitomagnetic structure

In Boyer-Lindquist coordinates  $(t, r, \theta, \phi)$  the Kerr metric is

$$\begin{aligned} ds^2 = & - \left(1 - \frac{r_s r}{\Sigma}\right) c^2 dt^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2 \\ & + \left(r^2 + a^2 + \frac{r_s r a^2}{\Sigma} \sin^2 \theta\right) \sin^2 \theta d\phi^2 - \frac{2r_s r a \sin^2 \theta}{\Sigma} c dt d\phi, \end{aligned} \quad (9.107)$$

with

$$r_s = \frac{2GM}{c^2}, \quad (9.108)$$

$$\Sigma = r^2 + a^2 \cos^2 \theta, \quad (9.109)$$

$$\Delta = r^2 - r_s r + a^2, \quad (9.110)$$

$$a = \frac{J}{Mc}. \quad (9.111)$$

The mixed  $t\phi$ -term,

$$g_{t\phi} = - \frac{r_s r a \sin^2 \theta}{\Sigma} c, \quad (9.112)$$

encodes frame-dragging. The local angular velocity of zero-angular-momentum observers (ZAMOs) is

$$\Omega_{\text{FD}}(r, \theta) = -\frac{g_{t\phi}}{g_{\phi\phi}} = \frac{r_s a c r}{\Sigma (r^2 + a^2) + r_s a^2 r \sin^2 \theta}, \quad (9.113)$$

which behaves as  $\Omega_{\text{FD}} \sim (2GJ)/(c^2 r^3)$  for  $r \gg r_s$ . This  $1/r^3$  falloff is the familiar Lense–Thirring behavior.

#### 9.5.4 Inverse metric and key Christoffel symbols

To connect frame-dragging to curvature we need the inverse of the  $(t, \phi)$  sub-block of the metric. For a  $2 \times 2$  block with entries  $g_{00} = g_{tt}$ ,  $g_{0\phi} = g_{t\phi}$ ,  $g_{\phi\phi}$ , the inverse components are

$$g^{00} = -\frac{g_{\phi\phi}}{g_{00}g_{\phi\phi} - g_{0\phi}^2}, \quad g^{0\phi} = \frac{g_{0\phi}}{g_{00}g_{\phi\phi} - g_{0\phi}^2}, \quad g^{\phi\phi} = \frac{g_{00}}{g_{00}g_{\phi\phi} - g_{0\phi}^2}, \quad (9.114)$$

with

$$g_{00}g_{\phi\phi} - g_{0\phi}^2 = \Sigma \sin^2 \theta. \quad (9.115)$$

The Christoffel symbols are

$$\Gamma_{\mu\nu}^\lambda = \frac{1}{2} g^{\lambda\sigma} (\partial_\mu g_{\nu\sigma} + \partial_\nu g_{\mu\sigma} - \partial_\sigma g_{\mu\nu}). \quad (9.116)$$

Frame-dragging enters through symbols that mix  $t$  and  $\phi$  with spatial indices, such as

$$\Gamma_{0r}^\phi = \frac{1}{2} (g^{\phi\phi} \partial_r g_{0\phi} + g^{\phi 0} \partial_r g_{00}), \quad \Gamma_{0\theta}^\phi = \frac{1}{2} (g^{\phi\phi} \partial_\theta g_{0\phi} + g^{\phi 0} \partial_\theta g_{00}), \quad (9.117)$$

which quantify how rotation couples time and angle as a function of radius and latitude. These are nonzero in Kerr because  $g_{0\phi} \neq 0$ .

#### 9.5.5 Gravitomagnetic Riemann components

In vacuum Kerr,  $R_{\mu\nu} = 0$ , but the Riemann tensor  $R^\mu{}_{\nu\rho\sigma}$  (equivalently the Weyl tensor  $C^\mu{}_{\nu\rho\sigma}$ ) is nonzero and carries the true tidal information. Frame-dragging appears in components with one time index and one azimuthal index, for example

$$R^\phi{}_{0r\phi} = \partial_r \Gamma_{0\phi}^\phi - \partial_\phi \Gamma_{0r}^\phi + \Gamma_{r\lambda}^\phi \Gamma_{0\phi}^\lambda - \Gamma_{\phi\lambda}^\phi \Gamma_{0r}^\lambda. \quad (9.118)$$

In the far-field, slow-rotation regime ( $r \gg r_s$ ,  $a/r \ll 1$ ), keeping the leading terms in  $a$  and  $M$ , one finds schematically

$$R^\phi{}_{0r\phi} \sim -\frac{3GJ}{c^2 r^4} \sin^2 \theta + \mathcal{O}\left(\frac{GM}{c^2 r^4}\right), \quad (9.119)$$

up to numerical factors depending on the precise component chosen and index placement. The key features are:

- a  $J$ -dependent sign that reverses under  $J \rightarrow -J$ ,
- a  $1/r^4$  falloff consistent with a gravitomagnetic *tidal* field,
- a  $\sin^2 \theta$  factor, maximized at the equator.

Other mixed components, such as  $R^\theta{}_{0r\theta}$  or  $R^r{}_{0\theta r}$ , show the same qualitative behavior, rotated among spatial indices. Collectively, these encode the differential precession of nearby worldlines due to frame-dragging.

### 9.5.6 Foam-Plexus interpretation: twist density and tidal fields

In the Foam-Plexus description, the gravitational plexus is characterized, at coarse-grained scales, by:

- a scalar alignment density  $\rho_g(x)$  encoding the mass monopole and higher even multipoles, and
- a twist density  $\tau_g(x)$  (pseudoscalar or axial) encoding the spin dipole and higher odd multipoles.

For a rotating mass, their far-field behavior (derived from the harmonic Ernst potentials in Sec. 9.4.7) is

$$\rho_g(r, \theta) = \rho_0 + \chi_M \frac{M}{r} + \mathcal{O}(r^{-3}), \quad \tau_g(r, \theta) = \chi_J \frac{J}{r^2} \sin \theta + \mathcal{O}(r^{-3}), \quad (9.120)$$

with  $\chi_M, \chi_J$  susceptibilities fixed once and for all by the microphysics.

The constitutive relations that map foam variables to the metric in the stationary, axisymmetric case can be written (in Lewis-Papapetrou form) as

$$f(\rho, z) = 1 - \kappa_M (\rho_g(\rho, z) - \rho_0), \quad \omega(\rho, z) = \kappa_J \tau_g(\rho, z), \quad (9.121)$$

where  $f$  is the lapse and  $\omega$  the dragging potential (see Sec. 9.4.5). These, together with first-order equations for the conformal factor  $\gamma(\rho, z)$ , reproduce the Kerr metric when  $\rho_g$  and  $\tau_g$  solve the harmonic Ernst equations.

Under this map, the far-field gravitomagnetic tidal components, such as  $R^\phi_{0r\phi}$ , become functionals of the coarse-grained twist:

$$R^\phi_{0r\phi}[g(\rho_g, \tau_g)] \sim \mathcal{K} \frac{\partial}{\partial r} \left[ \frac{\tau_g(r, \theta)}{r} \right] + \dots, \quad (9.122)$$

with  $\mathcal{K}$  a composite susceptibility built from  $\kappa_M, \kappa_J, \chi_M, \chi_J$ . Using Eq. (9.120) gives

$$R^\phi_{0r\phi} \propto \frac{GJ}{c^2 r^4} \sin^2 \theta, \quad (9.123)$$

with the proportionality fixed by matching to the Kerr expression (9.119). Thus the gravitomagnetic curvature is precisely the macroscopic imprint of the twist density  $\tau_g$  in the gravitational plexus.

### 9.5.7 Foam corrections as Weyl perturbations

At leading order, the coarse-grained fields  $(\rho_g, \tau_g)$  follow from the stationary solutions of the effective free energy  $\mathcal{F}_g[\rho_g, \tau_g]$  introduced in Chapter 2 and refined in Secs. 9.4.6–9.4.8, subject to boundary conditions fixed by  $(M, J)$ . Small fluctuations  $\delta\rho_g, \delta\tau_g$  around these saddle points induce corrections

$$\delta C^\mu_{\nu\rho\sigma} \sim \frac{\partial C^\mu_{\nu\rho\sigma}}{\partial \rho_g} \delta\rho_g + \frac{\partial C^\mu_{\nu\rho\sigma}}{\partial \tau_g} \delta\tau_g, \quad (9.124)$$

which constitute a microscopic, foam-induced noise floor on top of the exact Kerr tidal field. Because the background Ricci vanishes, these corrections are most naturally interpreted as *Weyl* perturbations in the exterior region.

In particular, the fractional modulation of a given Riemann component may be estimated as

$$\frac{\delta R^\phi_{0r\phi}}{R^\phi_{0r\phi}} \sim \frac{\delta\tau_g}{\tau_g} \sim \epsilon_{\text{foam}}, \quad (9.125)$$

where  $\epsilon_{\text{foam}}$  is a dimensionless measure of relative twist fluctuations in a coarse cell. For plausible plexus parameters we expect  $\epsilon_{\text{foam}} \sim 10^{-5}$ , matching the scale of foam-induced gravitational-wave noise discussed below.

### 9.5.8 Testable prediction: frame-dragging noise in ringdown

The gravitomagnetic tidal field is directly probed by the angular structure and phase of gravitational waves from rotating compact objects. In the Foam-Plexus picture, the stochastic fluctuations of  $\tau_g$  near the saturation surface  $r \simeq r_+$  induce small phase and amplitude modulations of Kerr quasinormal modes.

Schematically, the strain tensor  $h_{\mu\nu}$  measured far from the source can be written as

$$h_{\mu\nu}(t, \Omega) = h_{\mu\nu}^{\text{Kerr}}(t, \Omega) [1 + \delta_{\text{FD}}(t, \Omega)], \quad (9.126)$$

with

$$\delta_{\text{FD}} \sim \epsilon_{\text{foam}} \sim 10^{-5}, \quad (9.127)$$

dominated by Weyl perturbations in the mixed time-angular components inherited from  $\delta\tau_g$ . The signal appears as a tiny, statistically stationary noise floor in the late-time ringdown, correlated with the spin parameter  $a$  and vanishing smoothly in the Schwarzschild limit  $a \rightarrow 0$ .

Third-generation observatories (Einstein Telescope, Cosmic Explorer) may be able to constrain or detect such a frame-dragging noise floor, providing a direct test of the Foam-Plexus microstructure in the gravitomagnetic sector.

## 9.6 Kerr Radial Curvature: $R^r_{\theta r \theta}$ and Weyl Structure

### 9.6.1 Introduction

The frame-dragging sector probes the mixed time–azimuthal components of the Weyl tensor (Sec. 9.5). Radial curvature, by contrast, probes the purely spatial, axisymmetric tidal fields of Kerr. These encode how nearby geodesics either focus or defocus in  $r$ – $\theta$  planes, and they reveal how rotation anisotropically modifies the spacetime’s gravitational “stiffness.”

Because Kerr is a vacuum solution for  $r > r_+$ ,

$$R_{\mu\nu} = 0 \quad (r > r_+), \quad (9.128)$$

the entire radial-curvature structure resides in the Riemann (equivalently, Weyl) tensor. The Foam–Plexus interpretation therefore treats radial curvature as a macroscopic manifestation of the alignment density  $\rho_g$  and its polar distortion induced by spin, complementing the twist-driven gravitomagnetic sector discussed previously.

### 9.6.2 Kerr metric recap

For radial curvature we continue to work with the Boyer–Lindquist form of the Kerr metric given in Eq. (9.107), with  $r_s$ ,  $\Sigma$ ,  $\Delta$  and  $a$  as defined there. The spatial curvature we will focus on resides in the  $(r, \theta)$  sector, through components of the form  $R^r_{\theta r \theta}$  and permutations.

### 9.6.3 Radial tidal curvature in vacuum Kerr

To isolate the radial tidal field we consider the Riemann component  $R^r_{\theta r \theta}$ , which measures how an initially circular bundle of geodesics in the  $r$ – $\theta$  plane distorts as it propagates radially. In the slow-rotation, far-field regime ( $a/r \ll 1$ ,  $r \gg r_s$ ), Kerr geometry gives, after evaluation of Christoffel symbols and derivatives,

$$R^r_{\theta r \theta} \simeq -\frac{GM}{c^2 r^3} + \frac{3GMa^2}{c^2 r^5} \cos^2 \theta + \mathcal{O}\left(\frac{a^4}{r^7}\right), \quad (9.129)$$

which captures the leading monopole and quadrupole structure of Kerr, correct through  $\mathcal{O}(a^2)$  in a slow-rotation, far-field expansion.

Several features are noteworthy:

- The Schwarzschild term ( $-GM/(c^2 r^3)$ ) is recovered when  $a \rightarrow 0$ .
- Rotation introduces an *anisotropic* correction proportional to  $\cos^2 \theta$ , reflecting the oblate quadrupole moment of Kerr.
- The structure is purely Weyl:  $R_{\mu\nu} = 0$  throughout  $r > r_+$ .

For  $r \gg r_s$ , the leading anisotropic curvature scales as

$$R^r_{\theta r \theta} \sim -\frac{GM}{c^2 r^3} \left[ 1 - 3 \frac{a^2}{r^2} \cos^2 \theta \right]. \quad (9.130)$$

The  $\theta$ -angle where the anisotropy changes sign is given by  $3 \cos^2 \theta = 1$ , the familiar “magic angle” of the Kerr tidal field.

### 9.6.4 Foam–Plexus interpretation: alignment density

In the coarse-grained Foam–Plexus model, the mass distribution of Kerr is encoded in the alignment density  $\rho_g(r, \theta)$ , which in the far field (obtained from the harmonic Ernst potential  $\mathcal{U}$ ) behaves as:

$$\rho_g(r, \theta) = \rho_0 + \chi_M \frac{M}{r} + \chi_{M,2} \frac{Ma^2}{r^3} P_2(\cos \theta) + \mathcal{O}(r^{-4}), \quad (9.131)$$

with  $P_2(\cos \theta) = \frac{1}{2}(3 \cos^2 \theta - 1)$  the quadrupole Legendre polynomial.

The key points of correspondence are:

- The monopole term  $\sim 1/r$  maps to the Schwarzschild tidal field.
- The quadrupole anisotropy  $\sim a^2 P_2(\cos \theta)/r^3$  exactly matches the angular structure of the Kerr quadrupole.
- The susceptibility  $\chi_{M,2}$  is fixed by matching the coefficient of  $R^r_{\theta r \theta}$  in (9.129).

Thus the radial tidal field is the macroscopic imprint of the polar variation of the alignment density  $\rho_g$ , once the angular momentum  $J$  has deformed its equipotential surfaces.

### 9.6.5 Constitutive correspondence

In stationary, axisymmetric spacetimes (Lewis–Papapetrou form), the lapse  $f(\rho, z)$  depends only on  $\rho_g - \rho_0$ :

$$f = 1 - \kappa_M(\rho_g - \rho_0), \quad (9.132)$$

while the dragging potential depends on the twist  $\tau_g$ . Radial curvature enters entirely through the  $f$  sector, hence through  $\rho_g$ .

The Riemann component  $R^r_{\theta r \theta}$  can be written schematically as

$$R^r_{\theta r \theta}[g(\rho_g)] = \mathcal{A}_1 \partial_r^2 \rho_g + \mathcal{A}_2 \frac{1}{r} \partial_r \rho_g + \mathcal{A}_3 \frac{1}{r^2} \partial_\theta^2 \rho_g + \dots \quad (9.133)$$

with coefficients  $\mathcal{A}_i$  determined by  $(\kappa_M, \chi_M)$  and the coordinate transformation to BL form. Substitution of (9.131) reproduces the Kerr expression (9.129) at the monopole and quadrupole orders relevant for the slow-rotation, far-field regime.

### 9.6.6 Foam corrections as Weyl perturbations

Fluctuations  $\delta\rho_g$  around the stationary solution introduce tiny corrections to the radial curvature:

$$\delta R^r_{\theta r \theta} = \frac{\partial R^r_{\theta r \theta}}{\partial \rho_g} \delta \rho_g + \frac{\partial R^r_{\theta r \theta}}{\partial (\partial \rho_g)} \partial \delta \rho_g + \dots \quad (9.134)$$

Because  $R_{\mu\nu} = 0$  in the exterior, these corrections do not appear as Ricci curvature; they manifest purely as Weyl perturbations:

$$\delta C^r_{\theta r \theta} \sim \epsilon_{\text{foam}} R^{\text{Kerr}}_{\theta r \theta}, \quad (9.135)$$

with

$$\epsilon_{\text{foam}} \equiv \frac{\delta \rho_g}{\rho_g - \rho_0} \sim 10^{-5}. \quad (9.136)$$

These fluctuations vanish with  $a \rightarrow 0$ , consistent with the Schwarzschild limit and with the suppression of quadrupolar anisotropy in the nonrotating case.

### 9.6.7 Testable prediction: radial Weyl noise

Radial curvature affects the relative stretching/squeezing of geodesic separation vectors. Foam fluctuations therefore induce small modulations in the polarization and phase of gravitational waves near the source.

For the strain tensor measured far away,

$$h_{\mu\nu}(t) = h^{\text{Kerr}}_{\mu\nu}(t) [1 + \delta_{\text{RC}}(t)], \quad (9.137)$$

with

$$\delta_{\text{RC}} \sim \epsilon_{\text{foam}} \sim 10^{-5}, \quad (9.138)$$

coming mainly from the quadrupolar sector of the radial Weyl curvature. Because this signal is aligned with the Kerr quadrupole, it complements the frame-dragging perturbations identified previously.

Near-future detectors (LIGO A+) may constrain this radial noise; third-generation observatories (Einstein Telescope, Cosmic Explorer) will be sensitive enough to test it directly.

### 9.6.8 Summary

Radial curvature in Kerr is a purely Weyl phenomenon whose multipole structure is captured by the alignment density  $\rho_g$ . The Schwarzschild monopole and Kerr quadrupole arise from the  $1/r$  and  $a^2 P_2(\cos \theta)/r^3$  terms of the coarse-grained Foam–Plexus density. Small foam fluctuations appear as Weyl perturbations  $\delta C^r_{\theta r \theta}$  of amplitude  $\sim 10^{-5}$ , providing a clean observational target in the radial tidal sector of gravitational waves and forming a natural counterpart to the gravitomagnetic noise discussed in Sec. 9.5.

## 9.7 Motion in the Foam-Plexus Model

*Notation:* Throughout this section we use  $\rho_{w_g}$  to denote the micro-level gravity wormhole density and  $\rho_g$  for its coarse-grained, continuum approximation. This convention follows the clarification given in the Kerr analysis, where  $\rho_{w_g}$  and  $\rho_g$  are related through coarse-graining of the wormhole ensemble.

### 9.7.1 Introduction

Motion in the Foam-Plexus Model does not consist of particles traveling through a pre-existing geometric manifold. Instead, every particle moves by repeatedly renewing its wormhole connections with the underlying quantum foam. Each renewal event establishes a new adjacency relation between the particle's perimeter loops and foam wormholes that satisfy its Plexus boundary conditions. Classical trajectories emerge statistically from this microscopic renewal mechanism, while quantum interference arises naturally from the superposition of all allowed reconnection sequences.

This section develops the general theory of motion applicable to photons, fermions, quarks, composite systems, and virtual excitations. The formalism unifies the effects introduced in Schwarzschild and Kerr and prepares the ground for the ergosphere and Penrose processes.

### 9.7.2 Stochastic Motion and Sum-over-Histories

A particle's worldline is not a continuous curve but a chain of wormhole reconnections. At each step, the particle's loop structure is renewed through a foam wormhole that

- matches the particle's Plexus topology,
- satisfies local resonance conditions, and
- offers sufficient stability to maintain the particle's identity.

Because foam wormholes appear and vanish stochastically, the particle effectively samples all possible renewal directions. The amplitude associated with any reconnection chain  $i$  is

$$\psi_i \propto e^{-r_i/\ell_P} e^{iE_w t/\hbar}, \quad (9.139)$$

where  $r_i$  is the effective wormhole path length,  $\ell_P$  is the Planck-scale correlation length, and  $E_w$  is the wormhole energy associated with the loop.

The observed amplitude arises from summing over all allowed reconnection sequences:

$$\Psi = \sum_i \psi_i. \quad (9.140)$$

This automatically reproduces the QED sum-over-histories and explains interference, diffraction, and entanglement as structural consequences of the foam's connectivity. A photon is therefore not a pointlike particle with a definite trajectory; it is a stable double-loop structure whose connectivity to the foam continuously changes. The "path" is an emergent property of the evolving network.

### 9.7.3 Gravity's Role: Modulating the Foam

Fermions contain Gravity-faces, which act as amplifiers for wormhole formation in the foam. Massive bodies therefore generate regions where the foam supplies wormholes at higher density and higher renewal rate. This structure is the Gravity-Plexus, which extends outward from matter.

Because the Gravity-Plexus modifies the foam itself, it influences the availability of all wormhole types:

- EM-compatible wormholes,
- Weak-compatible wormholes,
- Strong-compatible wormholes,
- Higgs-compatible wormholes.

Thus every Plexus acquires foam-induced gradients around massive bodies. Particles respond only to the wormholes matching their own topology. Gravity does not directly act on photons or quarks or electrons. Instead, it modifies the availability landscape through which their loop renewals occur.

### 9.7.4 EM-Plexus Gradients Near Massive Bodies

The Electromagnetic Plexus consists of all foam wormholes capable of renewing EM perimeter loops. Because the Gravity-Plexus enhances wormhole formation near fermions, the density of EM-compatible wormholes increases around a massive body.

This forms a smooth EM-Plexus gradient.

Key properties include:

- it is not charge-specific,
- it supports both positive and negative EM-loop flows,
- and the photon's double-loop structure couples naturally to it.

The gradient exists simply because the foam offers EM-compatible wormholes at higher density nearer to matter.

### 9.7.5 Photon Motion in an EM-Plexus Gradient

A photon never travels as a point. Instead, it propagates by renewing its EM loops through EM-consistent wormholes provided by the foam. Since these wormholes are more abundant in certain directions, the photon's renewal process becomes directionally biased.

#### Mechanism

1. The photon stochastically samples all possible renewal directions.
2. Directions with higher EM-wormhole density produce more renewal options.
3. These options contribute larger amplitude weight in the sum-over-histories.
4. The classical photon path is the most probable renewal chain, biased toward massive bodies.

Thus,

gravity creates gradients in the EM-Plexus, and the photon's stochastic renewal process statistically favors paths along those gradients.

This reproduces gravitational lensing without requiring spacetime curvature as a fundamental entity, without any gravitational force acting on the photon, and without mixing Plexus topologies.

### 9.7.6 Generalized Motion for Any Particle

The same reasoning applies universally:

- Electrons follow gradients in both EM-Plexus and Gravity-Plexus.
- Neutrinos follow Weak-Plexus gradients shaped by the underlying foam.
- Quarks follow Strong-Plexus gradients inside hadrons.
- Composite systems follow the combined gradients of all constituent Plexuses.
- Fermions follow Gravity-Plexus gradients directly due to their Gravity-faces.

Thus every classical trajectory—massive or massless—emerges from:

1. gravity-induced modulation of the foam,
2. Plexus-specific wormhole gradients,
3. stochastic renewal of loop structures,
4. sum-over-histories interference,
5. selection of the most probable renewal path.

GR geodesics become the macroscopic limit of wormhole-density-optimized motion.

### 9.7.7 Motion and Curvature in the Foam–Plexus Model

In this framework:

- “Curvature” is not a property of spacetime as manifold.
- It is a property of wormhole-density gradients in the quantum foam.
- Geodesics arise statistically from renewal probabilities.
- Forces emerge from Plexus-specific gradients generated indirectly by gravity.

This reframes motion as a fundamentally quantum-topological phenomenon, with classical behavior emerging naturally in the limit of large-scale wormhole statistics.

### 9.7.8 Summary

Motion in the Foam–Plexus Model is the renewal of loop structures through wormholes supplied by the quantum foam. Gravity modifies the foam, creating Plexus-specific gradients. Photons, electrons, neutrinos, and quarks follow these gradients probabilistically, with classical trajectories emerging as the most probable chains of wormhole reconnection events.

This section unifies quantum behavior (interference, sum-over-histories), classical behavior (geodesics, lensing, inertia), gravitational behavior (wormhole-density modulation), and Plexus-based forces (EM, Weak, Strong, Higgs) under a single, consistent mechanism of motion.

## 9.8 Ergosphere Dynamics in the Foam–Plexus Model

*Notation:* Throughout this section we use  $\rho_{w_g}$  to denote the micro-level gravity wormhole density and  $\rho_g$  for its coarse-grained, continuum approximation. This convention follows the clarification given in the Kerr analysis, where  $\rho_{w_g}$  and  $\rho_g$  are related through coarse-graining of the wormhole ensemble.

### 9.8.1 Introduction

Kerr’s ergosphere—the region where no timelike worldline can remain stationary—arises in GR from the intense rotational coupling encoded in the off-diagonal metric term  $g_{0\phi}$ . In the Foam–Plexus interpretation, this behavior emerges from *directionally biased wormhole statistics*: the Gravity-Plexus sourced by rotating fermionic matter produces azimuthally aligned wormhole-density gradients. These gradients force all particles—photon or massive—to renew their loops along co-rotating paths, reproducing frame-dragging and the ergosphere’s “no static observers” condition.

This section updates the ergosphere analysis to integrate the general Motion formalism: particles follow the most probable wormhole-renewal chains, and the ergosphere’s structure is understood as a region where *all available renewal paths possess net angular momentum*.

### 9.8.2 Ergosphere Geometry Recap

The ergosphere extends from the outer horizon  $r_+$  to the boundary where  $g_{00} = 0$ :

$$r_E(\theta) = \frac{r_s}{2} + \sqrt{\frac{r_s^2}{4} - \alpha^2 \cos^2 \theta}, \quad (9.141)$$

with  $r_s = \frac{2GM}{c^2}$  and  $\alpha = \frac{J}{Mc}$ . In GR, this is where the rotational frame-dragging forces all observers to co-rotate.

In the Foam–Plexus model, this boundary corresponds to the radius where the *azimuthal wormhole-alignment term* overwhelms radial and static components, making *all* allowed reconnection sequences have  $u^\phi > 0$ .

### 9.8.3 Wormhole Topology and Rotational Alignment

The wormhole density in the Gravity-Plexus includes rotation-induced alignment:

$$\rho_{w_g}(r, \theta) = \rho_0 + \mathcal{R}_g \tau_g \frac{BM}{r} + \mathcal{R}_g \tau_g \frac{CJ}{r^2} \sin \theta, \quad (9.142)$$

where:

- $\rho_0$  is the baseline foam density,
- the  $BM/r$  term gives static (Schwarzschild-like) curvature,
- the  $CJ/r^2$  term encodes rotational alignment of wormholes.

The key update: **this alignment is not a force**, and it does not “drag” particles directly. It *tilts the wormhole density gradient* so that *most* valid reconnection paths point azimuthally.

Thus, the classical frame-dragging angular velocity

$$\omega = -\frac{g_{0\phi}}{g_{\phi\phi}}$$

is recovered statistically as the dominant directional renewal rate.

Near the ergosphere ( $r_+ < r < r_E$ ), the allowed renewal paths satisfying Plexus constraints all share:

$$u^\phi > 0,$$

which is the Foam–Plexus equivalent of GR’s “no static observers.”

### 9.8.4 Particles in the Ergosphere: Renewal Paths Under Directional Constraint

Using the Motion formalism, a particle explores all possible wormhole renewal sequences. Inside the ergosphere:

- azimuthally forward wormholes overwhelmingly dominate, - backward (counter-rotating) reconnections exist but have exponentially suppressed amplitude, - thus the classical trajectory emerges as a co-rotating path.

A photon experiences this through EM-Plexus gradients:

- gravity enhances EM-compatible wormholes, - rotation skews their angular distribution, - the photon's most probable renewal chain follows the skew.

Electrons and fermions additionally respond directly to Gravity-Plexus gradients.

Quarks respond to strong-Plexus gradients inside hadrons but macroscopically follow the same skewed distribution.

Thus, the ergosphere is the region where:

*All Plexus-specific gradients share a common rotational bias, forcing every particle's most probable motion to co-rotate.*

### 9.8.5 Penrose Process in the Foam-Plexus

In GR, the Penrose process exploits negative-energy trajectories ( $E < 0$ ) inside the ergosphere. In the Foam-Plexus model, these correspond to renewal sequences where:

- the particle's loop structure connects preferentially to wormholes that *offload angular momentum* into the rotating foam, - reducing the particle's net energy as measured at infinity.

The energy expression

$$E = -p_0 = -g_{0\mu}p^\mu \quad (9.143)$$

acquires its sign from whether the wormhole-aligned renewal sequence produces net forward or backward angular momentum relative to the rotating foam environment.

A particle splitting into two inside the ergosphere corresponds to:

- one branch adopting a renewal chain with  $E < 0$  (absorbing angular momentum into the foam), - the other adopting a chain with  $E > E_{\text{initial}}$ .

Thus, the Penrose process becomes:

*The statistical selection of diverging renewal chains, one aligned with negative-energy wormhole configurations and another with positive-energy ones.*

No new forces or fields are introduced: the process emerges from directional wormhole supply and Plexus boundary conditions.

### 9.8.6 Integration with Foam Dynamics

Foam fluctuations amplify the rotational term in  $\rho_{wg}$  as  $J$  increases. This reinforces frame-dragging and matches the analysis of  $R_{0\phi}$  from the Kerr chapter. When averaged over all reconnection paths, this yields the expected GR curvature statistics.

Because particles follow the Motion rules (sum over wormhole renewals), the ergosphere's global structure emerges naturally from the gradient landscape.

### 9.8.7 Testable Prediction

The rotational wormhole-alignment term induces a small but measurable modulation in gravitational wave signals:

$$\Delta h_{\mu\nu} \sim \frac{\mathcal{R}_g \tau_g C J}{c^3 r^2} h_{\mu\nu}, \quad \Delta h/h \sim 10^{-5}. \quad (9.144)$$

This represents a *rotation-dependent* perturbation distinct from radial curvature or frame-dragging noise. Detection at the  $10^{-5}$  level is consistent with LIGO-class sensitivity.

Observing such modulation would directly probe the Foam-Plexus interpretation of Kerr rotation.

## 9.9 Penrose Process Quantification

*Notation:* Throughout this section we use  $\rho_{w_g}$  to denote the micro-level gravity wormhole density and  $\rho_g$  for its coarse-grained, continuum approximation. This convention follows the clarification given in the Kerr analysis, where  $\rho_{w_g}$  and  $\rho_g$  are related through coarse-graining of the wormhole ensemble.

### 9.9.1 Introduction

The Penrose process is the culmination of Kerr dynamics: energy extraction from a rotating black hole enabled by the unique structure of the ergosphere. In General Relativity, this arises because the off-diagonal metric term  $g_{0\phi}$  permits negative-energy trajectories inside the ergosphere. In the Foam-Plexus model, the same effect emerges from *directionally biased wormhole-renewal paths*. The rotating fermionic mass sources an azimuthally skewed Gravity-Plexus, which tilts the wormhole-density landscape. Inside the ergosphere, all allowed renewal sequences possess net co-rotation, while a small subset of counter-rotating renewal chains correspond to GR's negative-energy states.

This section quantifies the Penrose process and shows how energy extraction emerges naturally from wormhole alignment in a quantized spacetime, with no singularities required.

### 9.9.2 Penrose Process Mechanics

#### Setup and Energy Recap

Inside the ergosphere, at  $r = r_+ + \epsilon$  (with  $r_+$  solving  $\Delta = 0$ ), a particle's conserved energy is

$$E = -p_0 = mc^2 \left[ -\left(1 - \frac{r_s r}{\Sigma}\right) u^0 + \frac{r_s r \alpha \sin^2 \theta}{\Sigma} u^\phi \right], \quad (9.145)$$

where  $r_s = \frac{2GM}{c^2}$ ,  $\alpha = \frac{J}{Mc}$ ,  $\Sigma = r^2 + \alpha^2 \cos^2 \theta$ , and  $\Delta = r^2 - r_s r + \alpha^2$ . Because  $g_{00}$  becomes positive in the ergosphere, trajectories with  $u^\phi < 0$  can yield  $E < 0$ .

In the Foam-Plexus interpretation, such trajectories correspond to *rare renewal sequences that counter-rotate relative to the dominant azimuthal wormhole alignment*. They are allowed but exponentially suppressed.

#### Process Dynamics

A standard Penrose process proceeds:

- **Particle 1** enters with  $u_1^\phi \approx 0$  and energy  $E_1 = m_1 c^2$ .
- **Split:** At  $r = r_+ + \epsilon$ , the particle splits with conserved 4-momentum

$$p_1^\mu = p_2^\mu + p_3^\mu.$$

- **Particle 2** adopts a rare counter-rotating renewal chain ( $u_2^\phi < 0$ ) and thus falls inward with

$$E_2 = m_2 c^2 \left[ -\left(1 - \frac{r_s}{r_+}\right) u_2^0 + \frac{r_s \alpha}{r_+^2} u_2^\phi \right] < 0. \quad (9.146)$$

- **Particle 3** emerges following the most probable (co-rotating) renewal chain and escapes with

$$E_3 = E_1 - E_2 > E_1.$$

Thus, particle 3 extracts rotational energy from the black hole.

#### Wormhole-Driven Extraction

The Foam-Plexus model provides the microphysical substrate for the negative-energy channel. The wormhole density near a rotating mass is

$$\rho_{w_g}(r, \theta) = \rho_0 + \mathcal{R}_g \tau_g \frac{BM}{r} + \mathcal{R}_g \tau_g \frac{CJ}{r^2} \sin \theta, \quad (9.147)$$

with:

- $\rho_0$ : baseline foam density,
- $\mathcal{R}_g \tau_g \frac{BM}{r}$ : static curvature (Schwarzschild-like),
- $\mathcal{R}_g \tau_g \frac{CJ}{r^2} \sin \theta$ : azimuthal wormhole alignment (Kerr-like).

Inside the ergosphere: - Nearly all available wormholes point forward (co-rotation), - But a suppressed minority support backward reconnections.

These suppressed renewal sequences correspond exactly to the GR negative-energy states.  
The energy extraction magnitude is

$$\Delta E = -E_2 \propto \mathcal{R}_g \tau_g \frac{CJ}{r_+^2},$$

where:

- $C = \frac{3G}{c^3 \mathcal{R}_g \tau_g}$  (from Kerr curvature calibration),
- $J = Mac$  is black hole angular momentum,
- $r_+ = M + \sqrt{M^2 - a^2}$  is the outer horizon radius.

For a solar-mass black hole:

$$\Delta E \sim 0.1 m_1 c^2,$$

consistent with GR's maximum Penrose efficiency but here derived from discrete wormhole-alignment statistics.

### 9.9.3 Integration with Foam Dynamics

Foam fluctuations (Eqs. 2.2, 2.7) allow all renewal sequences to contribute amplitudes, but the azimuthal twist dramatically skews their weights. The negative-energy trajectory corresponds to a renewal path that injects angular momentum into the rotating Gravity-Plexus. The escaping particle's energy amplification naturally follows:

$$E_3 = E_1 - E_2.$$

Thus, the Penrose process is not a continuous-force phenomenon but a manifestation of *branching wormhole-renewal chains inside a biased foam environment*.

### 9.9.4 Testable Prediction

The azimuthal wormhole-alignment term induces measurable corrections to gravitational waves emitted from rapidly spinning black holes:

$$\Delta h_{\mu\nu} \sim \frac{\mathcal{R}_g \tau_g CJ}{c^3 r_+^2} h_{\mu\nu}, \quad \frac{\Delta h}{h} \sim 10^{-5}. \quad (9.148)$$

This modulation:

- arises from azimuthal wormhole bias ( $\propto J$ ),
- is distinct from radial-only or nonrotating curvature effects,
- should be observable with next-generation detectors.

Searching for this signature in binary mergers involving high-spin holes provides a direct test of the Foam-Plexus description.

### 9.9.5 Conclusion

The Penrose process, reinterpreted through wormhole-alignment mechanics, demonstrates that negative-energy states and energy extraction arise naturally in a quantized-foam description of Kerr spacetime. No singularities are required, Lorentz invariance is preserved, and gravitational-wave signatures offer observational validation. This completes our analysis of rotational Plexus mechanics: from frame-dragging to ergosphere constraints to the Penrose process itself.

# 10 Layered-Horizon Growth in the Foam–Plexus Model

## Abstract

Gravitational-wave events such as GW190521 reveal black holes with masses in the pair-instability gap ( $50\text{--}150 M_\odot$ ), where standard stellar evolution predicts no remnants. In the Foam–Plexus model, event horizons are not geometric places where “time stops” but statistical boundaries where the *outward renewal probability* of all particle-loop structures collapses to effectively zero. Infalling matter therefore piles up in nested shells, each trapped at the radius where its own outward renewal channel vanishes.

Starting from sub-gap seeds ( $\lesssim 50 M_\odot$ ), continuous accretion naturally produces intermediate-mass black holes through the formation of these frozen layers. The same renewal mechanism yields Hawking radiation as rare outward renewal paths and produces *cascade evaporation* as successive layers become unsuppressed. This model eliminates singularities, resolves the information problem through *layered holography*, and predicts detectable ringdown echoes from inter-layer density discontinuities.

## 10.1 Introduction

LIGO–Virgo events such as GW190521 [?] reveal mergers involving black holes of  $66$  and  $85 M_\odot$ , producing a  $142 M_\odot$  remnant—squarely in the pair-instability supernova (PISN) gap [? ?]. Standard stellar evolution cannot easily produce such objects without rare hierarchical mergers or primordial black holes.

In the Foam–Plexus framework, event horizons arise from the same wormhole-renewal dynamics that govern all motion (Chapter ??) and from the statistical definition of horizons as renewal-probability barriers (Section ??). Black holes therefore grow by accreting nested frozen layers, not by collapsing into singularities.

## 10.2 The Pair-Instability Gap and Its Resolution

PISN completely disrupt stars of  $\sim 100\text{--}250 M_\odot$ , yielding a predicted absence of black holes between  $\sim 50$  and  $150 M_\odot$ .

In the renewal picture, the resolution is simple and physical:

*Seeds below the gap just keep accreting. Each new shell of infalling matter reaches the radius where the Gravity-Plexus gradient suppresses its outward renewal probability to essentially zero. The shell freezes there. The horizon moves outward. No explosive pair-instability phase ever occurs.*

Thus an  $85 M_\odot$  black hole is simply a  $10\text{--}30 M_\odot$  seed that has accreted  $\sim 55\text{--}75 M_\odot$  in successive frozen layers over cosmic time—requiring no exotic astrophysics, only the statistical mechanics of renewal.

## 10.3 Layered Structure from Renewal Suppression

Each infalling shell enhances the Gravity-Plexus:

$$\rho_g(r) \rightarrow \rho_g(r) + \delta\rho_g. \quad (10.1)$$

This steepens all plexus gradients (EM, Weak, Strong, Higgs), suppressing outward renewal probability for subsequent material. The shell halts when its own outward renewal channel collapses:

$$P_{\text{out}}(r_i) \simeq \exp\left(-\frac{8\pi G M_{\text{enclosed}}(r_i) E}{\hbar c}\right) \ll 1. \quad (10.2)$$

Thus matter forms a sequence of frozen shells:

- Total mass  $M = M_{\text{seed}} + \sum \Delta M_k$ ,

- Observable radius  $r_s \approx 2GM/c^2$  (standard GR exterior),
- No singularity, only a compact seed plus concentric frozen layers,
- Interior average density  $\sim 10^{15} \text{ kg/m}^3$  for  $\sim 100 M_\odot$ .

Each layer is a distinct renewal-probability barrier.

## 10.4 Cascade Evaporation and Layered Thermodynamics

Hawking radiation is the thermal tail of rare outward renewal paths (Section ??). As the outer layer radiates, its Gravity-Plexus contribution weakens, raising its  $P_{\text{out}}$  and eventually dissolving the layer.

Evaporation proceeds as a *cascade*:

1. The outermost layer radiates until it evaporates.
2. The next layer becomes the new surface where  $P_{\text{out}} \approx 0$ .
3. The process repeats until the original compact seed is exposed.

### 10.4.1 Layered Holography and Entropy

In this framework, each horizon layer encodes only the information of the shell it bounds. The total entropy is a sum over layers:

$$S_{\text{total}} = \sum_i \frac{k_B c^3}{4\hbar G} A_i \geq \frac{k_B c^3}{4\hbar G} A_{\text{outer}}, \quad (10.3)$$

which exceeds the classical Bekenstein–Hawking value. During cascade evaporation, information is released layer-by-layer, avoiding firewalls or remnants.

## 10.5 Merger Dynamics of Layered Black Holes

When two layered objects merge (e.g., GW190521), their wormhole networks and frozen shells partially interpenetrate and reconfigure. The density discontinuities between layers act as partial reflectors, producing:

- ringdown echoes,
- phase shifts,
- small modulations of quasinormal-mode amplitudes.

The final object returns to a single layered configuration with a standard GR exterior.

## 10.6 Testable Predictions

- **Gravitational-wave echoes:** Inter-layer spacings  $\Delta r$  produce delays

$$\Delta t \sim \Delta r/c \sim 0.1 - 10 \text{ ms},$$

with fractional amplitudes

$$\Delta h/h \sim 10^{-5} - 10^{-4}.$$

These are within reach of third-generation detectors.

- **Stepwise Hawking spectrum:** Evaporation reveals successive layers, producing nonthermal structure superposed on the Hawking spectrum.
- **Enhanced population of 50–150  $M_\odot$  black holes:** The model predicts that black holes in the pair-instability gap should be common in GW catalogs.
- **No firewalls or singularities:** Quasinormal-mode spectra remain clean near plunge, reflecting standard exterior geometry with quantized interior layering.

## 10.7 Conclusion

The Foam-Plexus model reframes black holes from singularities surrounded by geometric horizons into layered statistical objects governed by renewal-probability barriers. Infalling matter freezes into concentric shells, allowing sub-gap seeds to grow into intermediate-mass black holes while avoiding pair-instability disruptions. Hawking radiation, evaporation, holography, and GW signatures all arise from the same wormhole-renewal dynamics.

The event horizon is not where “time stops.” It is where the foam simply *refuses to offer an outward path*.

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**Part III**

**ELECTROMAGNETISM**

# 11 Maxwell's Equations from the EM-Plexus

## 11.1 Introduction: EM as a Worked Example of the Coarse-Graining Chain

Chapter 2 developed the general chain:

Planck-scale wormholes  $\rightarrow \mathcal{Z}[\beta, \mu_\alpha] \rightarrow$  coarse fields  $(\rho_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}} \rightarrow$  Einstein and gauge actions.

Gravity was treated as the first worked example: gradients of the Gravity-Plexus density and alignment fields reproduced curvature and the Einstein equations in the long-wavelength limit.

Electromagnetism follows exactly the same logic, but with a different microscopic structure. Here the fundamental objects are *EM-loops* (closed perimeter loops of EM-compatible wormholes) that occupy the EM-faces of multi-loop fermions. These EM-loops renew via EM-compatible wormholes generated dynamically by the foam. When we coarse-grain over many renewal events, the EM-Plexus produces:

- a macroscopic charge density and four-current  $J^\mu(x)$ ,
- an EM connectivity tensor  $C_{\mu\nu}(x)$ ,
- and, after normalization, the standard electromagnetic field tensor  $F_{\mu\nu}(x)$ .

The Maxwell equations then appear as continuum balance and topology conditions for this connectivity, just as the Einstein equations appear from the Gravity-Plexus. In short, photons are collective excitations of the EM-Plexus, and charged particles are localized sources that continuously “pump” EM-connectivity into or out of the foam — exactly parallel to how masses pump gravity-wormholes.

## 11.2 EM-Loops as Microscopic Sources of Charge

At the microscopic level, electric charge is not a pointlike label but an emergent property of an *EM-loop* on a fermion's EM-face. An EM-loop is a directional perimeter flow on that face:

- the *orientation* of the loop encodes the sign of the charge (clockwise vs. counterclockwise  $\rightarrow$  positive vs. negative),
- the *loop multiplicity* determines the magnitude of the charge ( $|q|$  in integer multiples of  $e$ ). For fundamental fermions there is always a single EM-loop; composite systems can carry multiple net loops.

In the Foam-Plexus model, these EM-loops are the fundamental sources of electromagnetic structure. As in Chapter 2, an EM-loop cannot simply sit still: it must continually renew by attaching to EM-compatible wormholes in the foam.

Each renewal event on a given EM-face does two things:

1. It preserves the loop's topology (and therefore its charge) on the fermion face.
2. It draws in or expels a bit of EM-compatible wormhole connectivity from the surrounding foam, slightly reshaping the local EM-Plexus.

At the Planck scale this renewal pattern is highly stochastic; on larger scales it becomes an average source for EM-compatible wormholes.

### 11.2.1 From EM-Loops to Charge Density and Four-Current

Consider a coarse-graining cell of spacetime with volume  $V_c$  and duration  $\Delta t$  containing many charged fermions. Within this region, EM-loops on their EM-faces undergo a huge number of renewal events. Following the logic of Chapter 2, we define:

- the *charge density*  $\rho(x)$  as the coarse-grained density of net EM-loop orientation per unit volume, and

- the *current density*  $\mathbf{J}(x)$  as the coarse-grained flux of EM-loop orientation through that volume.

These combine into the usual four-current

$$J^\mu(x) = (\rho c, \mathbf{J}), \quad (11.1)$$

which is nothing more than the continuum description of how EM-loops are distributed and how their net orientation flows through spacetime.

When a single charged fermion persists for many renewal times, its EM-loop renewals trace out a well-defined trajectory through the foam. Coarse-graining over these discrete events yields a smooth worldline  $x^\mu(\tau)$  with four-velocity  $u^\mu = dx^\mu/d\tau$ . The standard covariant expression for the four-current is then recognized as the continuum limit of EM-loop renewal counting:

$$J^\mu(x) = \sum_a q_a \int d\tau_a u_a^\mu(\tau_a) \delta^{(4)}(x - x_a(\tau_a)), \quad (11.2)$$

where the sum runs over all charged particles  $a$ , each carrying net EM-loop strength  $q_a$ . Equation (11.2) is therefore not an axiom but a coarse-grained bookkeeping identity: it counts how EM-loop sources move through the foam. The compactness of U(1) — and thus photon masslessness and charge quantization — follows from the topological invariance of the EM-loop winding number under local renewal moves.

### 11.3 From EM-Loop Renewals to Connectivity Tensor

The foam responds to these microscopic EM-loop sources by supplying EM-compatible wormholes that connect neighboring spacetime quanta. As in Chapter 2, we now replace discrete wormholes with coarse-grained order parameters over  $V_c$ .

Besides the scalar EM-plexus density  $\rho_{\text{EM}}(x)$ , the oriented character of EM-compatible wormholes leads naturally to an antisymmetric *EM connectivity tensor*

$$C_{\mu\nu}(x) = -C_{\nu\mu}(x), \quad (11.3)$$

which measures the average density of EM-compatible wormhole flux through an infinitesimal area element in the  $\mu\nu$ -plane at point  $x$ . Intuitively,  $C_{\mu\nu}$  counts oriented EM wormholes piercing small two-surfaces, in the same way that magnetic flux counts field lines.

Conservation of EM-compatible connectivity plays the same role here that conservation of wormhole density played for gravity. The net EM-wormhole flux entering a region must balance the EM-loop sources within it. When we coarse-grain over many wormhole formation and decay events, this constraint becomes a simple balance equation:

$$\partial_\mu C^{\mu\nu}(x) = J^\nu(x), \quad (11.4)$$

which ties together:

- microscopic EM-loops on particle faces,
- their coarse-grained charge and current  $J^\nu(x)$ , and
- the EM-compatible wormhole connectivity encoded in  $C_{\mu\nu}(x)$ .

Equation (11.4) is the EM-plexus analogue of the gravity-plexus density relations in Chapter 2: it is the EM version of “what goes in must come out” for wormhole connectivity.

### 11.4 Identification of the Electromagnetic Field Tensor

We now identify the physical electromagnetic field tensor  $F_{\mu\nu}$  as the properly normalized connectivity tensor:

$$F_{\mu\nu}(x) = k_{\text{EM}} C_{\mu\nu}(x), \quad (11.5)$$

where  $k_{\text{EM}}$  is a constant fixed by matching to the Coulomb limit around a static point charge. Substituting (11.5) into the balance equation (11.4) gives

$$\partial_\mu F^{\mu\nu}(x) = k_{\text{EM}} \partial_\mu C^{\mu\nu}(x) = k_{\text{EM}} J^\nu(x). \quad (11.6)$$

Choosing

$$k_{\text{EM}} = \mu_0, \quad (11.7)$$

we obtain the *inhomogeneous Maxwell equations* in covariant form:

$$\partial_\mu F^{\mu\nu} = \mu_0 J^\nu. \quad (11.8)$$

The homogeneous Maxwell equations arise from the fact that EM-compatible wormholes form oriented loops in the foam. Locally, the net number of such loops piercing any closed two-surface is conserved. In discrete form this is a statement that there is no net “endpoint” of EM connectivity. Coarse-graining yields the continuum identity

$$\partial_{[\alpha} C_{\beta\gamma]} = 0, \quad (11.9)$$

where brackets denote antisymmetrization. Under the normalization (11.5) this becomes

$$\partial_{[\alpha} F_{\beta\gamma]} = 0, \quad (11.10)$$

which is equivalent to:

- absence of magnetic monopoles ( $\nabla \cdot \mathbf{B} = 0$ ),
- Faraday induction ( $\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0$ ).

Equations (11.8) and (11.10) are therefore not postulates. They are the continuum limit of:

$$\text{EM-loop sources on fermion faces} \rightarrow J^\mu(x) \rightarrow C_{\mu\nu}(x) \rightarrow F_{\mu\nu}(x).$$

## 11.5 3+1 Decomposition and Classical Maxwell Equations

In any inertial frame we write

$$E_i = F_{0i}, \quad B_i = -\frac{1}{2}\epsilon_{ijk}F_{jk}, \quad (11.11)$$

with  $\epsilon_{ijk}$  the Levi-Civita symbol. The covariant equations (11.8)–(11.10) then become the familiar Maxwell equations:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}, \quad (11.12)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (11.13)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad (11.14)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}. \quad (11.15)$$

Here  $\rho = J^0/c$  and  $\mathbf{J}$  is the spatial part of  $J^\mu$ . The empirical relation

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (11.16)$$

will be interpreted below as a property of the EM-Plexus elasticity.

Equations (11.12)–(11.15) are thus reinterpreted as the macroscopic limit of EM-loop renewals and EM-wormhole connectivity in the foam.

## 11.6 Wave Propagation and Emergent Light Speed

In vacuum ( $\rho = 0$ ,  $\mathbf{J} = 0$ ), the Maxwell equations yield the standard wave equations:

$$\nabla^2 \mathbf{E} - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0, \quad (11.17)$$

$$\nabla^2 \mathbf{B} - \frac{1}{c^2} \frac{\partial^2 \mathbf{B}}{\partial t^2} = 0. \quad (11.18)$$

In the Foam-Plexus framework this propagation speed is not fundamental. It arises from the effective stiffness of the EM-Plexus in the Landau-Ginzburg free energy of Chapter 2.

Schematically, the EM contribution to the effective free energy has the form

$$\mathcal{F}_{\text{EM}} \sim \frac{K_{\text{EM}}}{2} (\nabla \Phi_{\text{EM}})^2 + V_{\text{EM}}(\Phi_{\text{EM}}), \quad (11.19)$$

where  $\Phi_{\text{EM}}$  is the appropriate complex EM order parameter and  $K_{\text{EM}}$  is an EM stiffness determined by the microscopic wormhole ensemble. When rewritten in terms of  $F_{\mu\nu}$ , this yields the standard Maxwell action with an effective coupling set by  $K_{\text{EM}}$ , and the wave speed  $c$  in (11.16) encodes the emergent ratio of electric to magnetic response in the EM-Plexus.

## 11.7 Planck-Scale Fluctuations and Tiny Corrections

Because  $F_{\mu\nu}$  is a coarse-grained connectivity tensor, it describes an average over many EM-compatible wormholes. At very large scales this average is extremely sharp, but near the Planck scale there are residual statistical fluctuations. These can be modeled as tiny, stochastic corrections to the effective permittivity and permeability:

$$\epsilon_{\text{eff}} = \epsilon_0(1 + \delta_\epsilon), \quad \mu_{\text{eff}} = \mu_0(1 + \delta_\mu), \quad (11.20)$$

with  $|\delta_\epsilon|, |\delta_\mu| \ll 1$  and determined by foam jitter statistics. The effective propagation speed becomes

$$c_{\text{eff}} \approx \frac{1}{\sqrt{\mu_0 \epsilon_0}} (1 + \delta), \quad \delta \equiv -\frac{1}{2}(\delta_\epsilon + \delta_\mu), \quad (11.21)$$

so that  $c_{\text{eff}} \rightarrow c$  in the continuum limit. For wavelengths  $\lambda \gg \ell_P$ , central-limit arguments give

$$|\delta| \sim \left( \frac{\ell_P}{\lambda} \right)^\alpha, \quad \alpha \gtrsim 1, \quad (11.22)$$

placing  $|\delta|$  many orders of magnitude below current experimental bounds. Nevertheless, the existence of such Planck-suppressed effects provides a direct empirical link between Maxwell's equations and the underlying quantum foam.

## 11.8 Summary

Electromagnetism in the Foam-Plexus model is a worked example of the coarse-graining chain of Chapter 2:

- Microscopic EM-loops on fermion EM-faces act as the fundamental sources of charge.
- Their renewals through EM-compatible wormholes define a coarse-grained charge density and four-current  $J^\mu(x)$ .
- The EM-Plexus connectivity is encoded in an antisymmetric tensor  $C_{\mu\nu}(x)$  whose divergence is fixed by  $J^\mu$ .
- After normalization,  $F_{\mu\nu} = \mu_0 C_{\mu\nu}$  satisfies the covariant Maxwell equations

$$\partial_\mu F^{\mu\nu} = \mu_0 J^\nu, \quad \partial_{[\alpha} F_{\beta\gamma]} = 0,$$

which reduce in 3+1 form to the familiar Gauss, Faraday, and Ampère-Maxwell laws.

- The speed of light  $c = 1/\sqrt{\mu_0 \epsilon_0}$  emerges from the EM-Plexus stiffness, and Planck-scale foam jitter introduces only tiny, Planck-suppressed corrections.

Maxwell's equations are therefore not fundamental postulates but continuum balance and topology conditions for EM-Plexus connectivity, driven by EM-loops on fermion faces and coarse-grained exactly as in the Gravity-Plexus case. In the next chapters we will extend this EM-Plexus picture to quantum electrodynamics: virtual photons, loop corrections, and anomalous magnetic moments.

# 12 QED Foundations in the EM–Plexus

## 12.1 Introduction

In the previous chapter we derived Maxwell’s equations as the coarse–grained description of EM-compatible wormhole connectivity driven by microscopic EM-loops on fermion EM-faces. The electromagnetic field tensor  $F_{\mu\nu}$  emerged from an antisymmetric connectivity tensor  $C'_{\mu\nu}$ , and the four-current  $J^\mu$  arose from coarse–grained EM-loop renewal statistics.

Quantum electrodynamics (QED) describes how charged particles interact with quantized excitations of this field: virtual and real photons. In the Foam–Plexus model, these “photons” correspond to specific patterns of EM–Plexus wormhole fluctuations around EM-loops. In this chapter we lay the foundations of QED in this language, focusing on:

- how virtual photons arise as transient EM–wormhole structures, and
- how the electron’s anomalous magnetic moment  $g_e \approx 2.002\,319$  emerges from plexus fluctuations.

This provides a bridge between the EM–Plexus picture and standard QED loop corrections, and sets up the precision tests (electron and muon  $g - 2$ ) developed in Chapter ??.

## 12.2 Dirac Dynamics from Foam–Plexus Wormhole Statistics

Before focusing on virtual photons and  $g - 2$ , it is useful to recall that the *fermion field itself* already emerges from the Foam–Plexus framework as an effective Dirac spinor. Here we summarize the key steps and fix notation; the detailed microscopic derivation is developed in Ref. [Wilkins2026b] (in preparation).

Let  $\rho_w(x, t)$  denote the local density of wormholes contributing to tetrahedral (lepton) formation and let  $S(x, t)$  be the phase associated with perimeter flux on the tetrahedral faces. Conservation of total wormhole flux leads to a continuity equation

$$\partial_t \rho_w + \nabla \cdot \mathbf{J}_w = 0, \quad \mathbf{J}_w = \frac{1}{m} \nabla S, \quad (12.1)$$

where  $m$  is the effective inertial mass generated by Higgs–plexus coupling.

Treating  $\sqrt{\rho_w}$  and  $S$  as canonical variables, one can write a schematic amplitude–phase Lagrangian density

$$\mathcal{L} = i\hbar \sqrt{\rho_w} \partial_t \sqrt{\rho_w} + i \rho_w \partial_t S - \frac{\hbar^2}{2m} |\nabla \sqrt{\rho_w}|^2 - \frac{1}{2m} (\nabla S)^2 - V \rho_w, \quad (12.2)$$

with  $V$  collecting effective interactions from other plexuses (e.g. Higgs and EM couplings). Varying with respect to  $\sqrt{\rho_w}$  and  $S$  yields coupled amplitude–phase equations which can be recombined into a single complex field

$$\psi(x, t) = \sqrt{\rho_w(x, t)} e^{iS(x, t)/\hbar}. \quad (12.3)$$

In the nonrelativistic limit this field obeys a Schrödinger–type equation

$$i\hbar \partial_t \psi = \left( -\frac{\hbar^2}{2m} \nabla^2 + V \right) \psi, \quad (12.4)$$

showing explicitly how a wavefunction arises from wormhole statistics.

Imposing lattice Lorentz invariance at the foam level and incorporating the tetrahedral spin structure (flux reversal under  $360^\circ$ , chirality set by the relative orientation of Weak and Higgs faces) promotes  $\psi$  to a four-component spinor  $\psi_\alpha$  and upgrades Eq. (12.4) to the relativistic Dirac form

$$(i\gamma^\mu \partial_\mu - m) \psi = 0, \quad (12.5)$$

where the spinor indices encode the two chiralities and particle/antiparticle components of a tetrahedral fermion. Electromagnetic coupling is then introduced via the usual minimal substitution

$$\partial_\mu \rightarrow D_\mu \equiv \partial_\mu + i \frac{q}{\hbar} A_\mu, \quad (12.6)$$

giving

$$(i\gamma^\mu D_\mu - m) \psi = 0. \quad (12.7)$$

In the Foam–Plexus language, Eq. (12.7) says:

- The spinor field  $\psi$  is the coarse-grained description of tetrahedral wormhole configurations and their perimeter flux.
- The mass term  $m$  encodes Higgs-plexus density gradients on the Higgs face.
- The EM potential  $A_\mu$  summarizes the coarse-grained EM-plexus connectivity  $C_{\mu\nu}$  generated by EM-loops on fermion faces.

The remainder of this chapter takes Eq. (12.7) as given and studies how EM-plexus fluctuations (virtual photons) dress this Dirac fermion, producing the observed anomalous magnetic moments for the electron and muon.

### 12.3 The Electron's Static EM-Plexus Dress

At the microscopic level the electron is a multi-loop fermion with a single EM-loop on its EM-face, oriented to give charge  $q_e = -e = -1.602 \times 10^{-19}$  C and spin  $S = \hbar/2$ . Coarse-graining the EM-compatible wormholes that renew this loop produces an EM-plexus density profile  $\rho_w^e(r)$ .

For a static electron at the origin, we model the EM-compatible wormhole density as

$$\rho_w^e(r) = \rho_0 + \mathcal{R}_e \tau_e \frac{A q_e}{r^2}, \quad \mathbf{E}(r) = -\frac{q_e}{4\pi\epsilon_0 r^2} \hat{\mathbf{r}}, \quad (12.8)$$

with

$$\mathcal{R}_e \tau_e A = \frac{1}{4\pi\epsilon_0}. \quad (12.9)$$

Here:

- $\rho_0$  is the baseline EM-compatible wormhole density of the foam,
- $\mathcal{R}_e$  is the EM-wormhole formation rate in the electron's vicinity,
- $\tau_e$  is the characteristic EM renewal time around the electron,
- $A$  is a geometric coupling factor encoding how EM-loops recruit wormholes.

The  $1/r^2$  falloff arises from the spherical symmetry of single-loop renewal averaging, while the spin alignment below introduces an additional  $1/r^3$  dipole structure.

The electron's spin  $S = \hbar/2$  introduces an additional, dipole-like alignment of EM-compatible wormholes. At leading order we write

$$\rho_w^S(r, \theta) = \mathcal{R}_e \tau_e \frac{BS}{r^3} \cos \theta, \quad (12.10)$$

with  $B$  (units  $\text{m}^{-2}\text{s}^{-1}$ ) characterizing the spin-plexus coupling and  $\theta$  the angle relative to the spin axis. Together, Eqs. (12.8) and (12.10) define the static EM-plexus “dress” of the electron.

### 12.4 Virtual Photons as EM-Plexus Fluctuations

In standard QED, virtual photons are internal lines in Feynman diagrams: off-shell quanta mediating interactions and dressing the electron. Here, the same physics is expressed in terms of EM-plexus fluctuations around the static profiles above.

Foam jitter (Sec. 2, Eq. 2.2) drives stochastic variations in the local EM-compatible wormhole population. Around an electron this yields a fluctuation

$$\Delta\rho_w(r) \sim \mathcal{R}_e \tau_e^2 \frac{A^2 q_e^2}{\hbar r^3}, \quad (12.11)$$

(up to angular factors) representing the temporary creation of additional EM-compatible wormholes that do *not* correspond to a stable EM-loop on any fermion face. These transient EM-only structures are identified with virtual photons in the usual QED language.

The characteristic energy scale associated with such a fluctuation over a renewal time  $\tau_e$  is

$$\Delta E \sim \frac{\hbar}{\tau_e}, \quad (12.12)$$

consistent with the uncertainty principle. For  $\tau_e$  chosen to match the electron Compton timescale, this energy is of order  $m_e c^2$ , in line with the usual QED picture that virtual photons probing the electron's structure are governed by the same mass scale.

Thus virtual photons correspond to short-lived, EM-only wormhole patterns generated and destroyed by foam jitter in the EM-Plexus, with statistics controlled by  $\mathcal{R}_e$  and  $\tau_e$ .

## 12.5 Spin Coupling and the Electron Magnetic Moment

The electron's magnetic moment is classically

$$\vec{\mu} = g_e \frac{e}{2m_e} \vec{S}, \quad (12.13)$$

with Dirac theory predicting  $g_e = 2$  for a pointlike spin- $\frac{1}{2}$  particle. Quantum electrodynamics adds the well-known anomaly

$$a_e \equiv \frac{g_e - 2}{2} \approx 0.001159652, \quad a_e = \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2), \quad \alpha = \frac{e^2}{4\pi\epsilon_0\hbar c}, \quad (12.14)$$

where  $\alpha$  is the fine structure constant.

In the EM-Plexus picture, the Dirac value  $g_e = 2$  arises from the coherent coupling between:

- the electron's spin-induced EM-wormhole alignment  $\rho_w^S$  in Eq. (12.10), and
- the static Coulomb-like density  $\rho_w^e$  in Eq. (12.8).

This defines an effective spin-EM coupling  $B$  in the absence of foam jitter. When EM-plexus fluctuations  $\Delta\rho_w$  (virtual photons) are included, the *average* spin coupling is shifted by a small amount  $\Delta B$ , leading to a shift in the magnetic moment.

At leading order, the anomaly can be parametrized as

$$a_e = \frac{\mathcal{R}_e \tau_e^2 A^2 B_{\text{eff}}}{\hbar}, \quad B_{\text{eff}} = B + \Delta B, \quad (12.15)$$

where  $B_{\text{eff}}$  encodes the combined effect of the static spin alignment and the correlated EM-plexus fluctuations. Matching to the one-loop QED result fixes

$$\frac{\mathcal{R}_e \tau_e^2 A^2 B_{\text{eff}}}{\hbar} = \frac{\alpha}{2\pi} + \mathcal{O}(\alpha^2), \quad (12.16)$$

providing a direct dictionary between the foam parameters  $(\mathcal{R}_e, \tau_e, A, B_{\text{eff}})$  and the standard perturbative QED expansion. Thus the Schwinger term  $\alpha/2\pi$  is not a radiative correction in the usual sense, but the back-reaction of the electron's own EM-plexus jitter on its spin precession.

## 12.6 Integration with Foam Dynamics and Lorentz Invariance

Foam jitter, introduced in Chapter 2 (Eq. 2.2), drives the fluctuations  $\Delta\rho_w$  that we identify with virtual photons. Because the underlying wormhole ensemble is constructed to be Lorentz-invariant (Eq. 2.11), the resulting EM-plexus fluctuations and their contribution to  $a_e$  inherit this invariance. In particular:

- the four-current  $J^\mu$  remains conserved,  $\partial_\mu J^\mu = 0$ ,
- the connectivity tensor  $C_{\mu\nu}$  transforms as a rank-2 antisymmetric tensor,
- the effective action for  $F_{\mu\nu}$  reduces in the long-wavelength limit to the standard Lorentz-invariant Maxwell-QED form.

Thus QED loop effects are reinterpreted as Lorentz-covariant statistics of EM-compatible wormhole oscillators and their coupling to EM-loops on fermion faces.

## 12.7 Planck–Scale Corrections and a Tiny Deviation

The leading anomaly  $a_e \simeq \alpha/(2\pi)$  is fixed by matching to standard QED. However, the Foam–Plexus model also allows for *discrete* corrections arising from the finite renewal time  $\tau_e$  and the underlying lattice structure at the Planck scale.

A natural dimensionless estimate for such a correction is

$$\Delta a_e \sim \frac{\hbar}{\tau_e m_e c^2}, \quad (12.17)$$

which measures the ratio between the renewal energy scale  $\hbar/\tau_e$  and the electron rest energy  $m_e c^2$ . For renewal times  $\tau_e$  chosen to match the Compton scale, this yields

$$\Delta a_e \sim 10^{-20}, \quad (12.18)$$

far below current experimental sensitivity but, in principle, a distinctive signature of foam discreteness in future ultra-precise experiments. This scale is beyond current capabilities, but it is not obviously out of reach for aggressive next-generation Penning-trap concepts.

## 12.8 Dictionary with Standard QED

It is useful to make the correspondence between standard QED language and the EM–Plexus picture explicit. Table 12.1 summarizes the key identifications.

| Standard QED Object                   | Foam–Plexus Interpretation                                                                                                                                                                            |
|---------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Virtual photon (off-shell line)       | Transient EM-only wormhole fluctuation $\Delta\rho_w$ in the EM–Plexus around EM-loops.                                                                                                               |
| Vertex correction                     | Modified renewal statistics at the junction where an EM-loop on a fermion face couples to EM-compatible wormhole patterns in the foam.                                                                |
| Vacuum polarization                   | Baseline foam jitter response of $\rho_0$ and $\rho_w^e$ to a passing EM-loop, altering the effective stiffness of the EM–Plexus and screening charge at different scales (Uehling–Serber potential). |
| Photon propagator                     | Long-range correlation function of EM-wormhole connectivity, i.e. the two-point function of $C_{\mu\nu}$ (or $F_{\mu\nu}$ ) induced by foam statistics.                                               |
| One-loop Schwinger term $\alpha/2\pi$ | Back-reaction shift $\Delta B/B$ in the effective spin–plexus coupling induced by jitter-averaged virtual-photon fluctuations.                                                                        |

Table 12.1: Dictionary between standard QED objects and their Foam–Plexus interpretations.

In this view, Feynman diagrams are a computational shorthand for the statistics of wormhole renewal, rather than a literal microscopic ontology. The plexus picture supplies that ontology: loops, faces, and foam dynamics.

## 12.9 Summary

In this chapter, QED emerges as the quantum theory of EM–Plexus fluctuations:

- EM-loops on fermion EM-faces source the static EM–plexus density  $\rho_w^e$  and spin alignment  $\rho_w^S$ .
- Foam jitter generates transient EM-only wormhole patterns  $\Delta\rho_w$ , identified with virtual photons.
- The Schwinger anomaly  $a_e \simeq \alpha/(2\pi)$  emerges as the average shift in spin–plexus coupling induced by virtual-photon fluctuations.

- Planck-scale discreteness introduces a tiny correction  $\Delta a_e \sim 10^{-20}$ , providing a potential (though extremely challenging) experimental probe of the foam.

This sets the stage for the next chapter, where the same EM-Plexus framework is applied to the muon's anomalous magnetic moment and other precision QED observables.

# 13 QED Precision: Muon $g-2$ in the Foam–Plexus Model

## 13.1 Introduction: Muon $g-2$ as a High–Precision Probe

The muon is a heavy copy of the electron with the same charge but a mass larger by a factor of  $\sim 207$ . Its anomalous magnetic moment,

$$a_\mu \equiv \frac{g_\mu - 2}{2}, \quad (13.1)$$

is one of the most precisely measured quantities in particle physics and a traditional window on physics beyond the Standard Model (SM).

The current world average from the BNL E821 and Fermilab E989 experiments yields

$$a_\mu^{\text{exp}} = 116\,592\,070.5(14.4) \times 10^{-11}, \quad (13.2)$$

with a relative precision at the level of a few parts in  $10^7$ . Recent SM updates, incorporating improved lattice-QCD evaluations of the leading-order hadronic vacuum polarization, give

$$a_\mu^{\text{SM}} = 116\,592\,033(62) \times 10^{-11}, \quad (13.3)$$

so that

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 38(63) \times 10^{-11}, \quad (13.4)$$

showing no statistically significant tension at the current level of precision.<sup>1</sup>

In the Foam–Plexus framework the muon provides a nontrivial cross-check of the EM–plexus dynamics introduced for the electron. The same microscopic mechanism that produces the electron Schwinger term  $\alpha/2\pi$  must also produce the leading QED contribution to  $a_\mu$ , while any foam-specific corrections must lie safely below the current experimental and theoretical uncertainties. This chapter shows how this works.

## 13.2 The Muon’s Static EM–Plexus Dress

The analysis parallels the electron case (Chapter ??). The muon carries the same electric charge as the electron,

$$q_\mu = q_e = -e, \quad (13.5)$$

but has a larger mass,

$$m_\mu \approx 105.66 \text{ MeV}/c^2. \quad (13.6)$$

The muon’s EM-loop on its EM-face drives an EM–plexus response of the form

$$\rho_w^\mu(r) = \rho_0 + \mathcal{R}_\mu \tau_\mu \frac{A q_\mu}{r^2}, \quad \mathbf{E}_\mu(r) = -\frac{q_\mu}{4\pi\epsilon_0 r^2} \hat{\mathbf{r}}, \quad (13.7)$$

where:

- $\rho_0$  is the baseline EM–plexus wormhole density,
- $\mathcal{R}_\mu$  is the local formation rate of EM-compatible wormholes driven by the muon’s EM-loop,
- $\tau_\mu$  is the characteristic renewal timescale of the muon’s EM-loop,
- $A$  is the same normalization constant that appeared in the electron case.

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<sup>1</sup>Numerical values from the 2025 SM whitepaper and the final combined Fermilab result.

As for the electron, the Coulomb law emerges once we impose

$$\mathcal{R}_\mu \tau_\mu A = \frac{1}{4\pi\epsilon_0}, \quad (13.8)$$

so the static EM field is identical in form. The difference between electron and muon lies in the detailed renewal statistics, not in the long-range Coulomb profile.

Spin adds a dipolar component to the EM-plexus density:

$$\rho_w^{S,\mu}(r, \theta) = \mathcal{R}_\mu \tau_\mu \frac{BS_\mu}{r^3} \cos \theta, \quad S_\mu = \frac{\hbar}{2}, \quad (13.9)$$

where  $B$  is the spin-plexus coupling constant already introduced for the electron. The  $\cos \theta$  dependence reflects the alignment of EM-compatible wormholes with the muon's spin axis.

### 13.3 Virtual Photon Jitter Around a Muon

Virtual photons in the Foam-Plexus picture are transient EM-only wormhole loops that nucleate and decay in the foam around charged EM-loops (Chapter ??). For the muon, the virtual-photon contribution to the EM-plexus density can be written schematically as

$$\Delta \rho_w^\mu(r) \sim \mathcal{R}_\mu \tau_\mu^2 \frac{A^2 q_\mu^2}{\hbar r^3}, \quad (13.10)$$

up to angular factors that encode the detailed pattern of wormhole alignment. The  $\tau_\mu^2$  factor reflects the fact that a full virtual loop involves both nucleation and decay within the EM-plexus renewal timescale.

Foam jitter (Chapter 2) continually perturbs the baseline density  $\rho_0$ , and the superposition of these fluctuations with the static spin-induced term  $\rho_w^{S,\mu}$  produces a small back-reaction on the effective spin-plexus coupling. This is the Foam-Plexus analog of the vertex correction that generates the Schwinger term in standard QED.

The effective local spin-coupling is

$$B_\mu^{\text{eff}} = B + \Delta B_\mu, \quad (13.11)$$

where the correction  $\Delta B_\mu$  is driven by the correlation between the spin dipole density and the virtual-photon cloud,

$$\Delta B_\mu \sim k_\mu \langle \nabla \rho_w^{S,\mu} \times \Delta \rho_w^\mu \rangle_{\text{foam}}, \quad (13.12)$$

with  $k_\mu$  a dimensionful coefficient encoding the stiffness of the EM-plexus under spin-induced shear. The expectation value is taken over foam jitter, much as in the electron case.

### 13.4 Universality of the Schwinger Term

In standard QED, the leading one-loop contribution to the anomalous magnetic moment is

$$a_\ell^{(1)} = \frac{\alpha}{2\pi}, \quad \ell = e, \mu, \tau, \quad (13.13)$$

independent of the lepton mass. Higher-order QED, electroweak, and hadronic contributions introduce lepton-dependent corrections, but the Schwinger term itself is universal.

In the Foam-Plexus model this universality is enforced by a simple scaling assumption for  $\mathcal{R}_\ell$  and  $\tau_\ell$ . Let the EM-loop renewal timescale for a lepton  $\ell$  be proportional to its Compton time,

$$\tau_\ell = \kappa_\tau \frac{\hbar}{m_\ell c^2}, \quad (13.14)$$

and let the EM-compatible wormhole formation rate scale as

$$\mathcal{R}_\ell = \kappa_R \frac{m_\ell^2 c^4}{\hbar^2}, \quad (13.15)$$

with  $\kappa_\tau$  and  $\kappa_R$  universal constants of the foam. Then the key combination that enters the anomalous moment,  $\mathcal{R}_\ell \tau_\ell^2$ , is lepton independent:

$$\mathcal{R}_\ell \tau_\ell^2 = \kappa_R \kappa_\tau^2, \quad (13.16)$$

the same for electron, muon, and tau. As a result, the Foam-Plexus expression for the leading EM-plexus contribution,

$$a_\ell^{\text{plexus}} = \frac{\mathcal{R}_\ell \tau_\ell^2 A^2 B}{\hbar} = \frac{\kappa_R \kappa_\tau^2 A^2 B}{\hbar}, \quad (13.17)$$

is universal across leptons. Calibrating to the electron fixes

$$a_e^{\text{plexus}} = \frac{\alpha}{2\pi} \implies \frac{\kappa_R \kappa_\tau^2 A^2 B}{\hbar} = \frac{\alpha}{2\pi}, \quad (13.18)$$

and therefore

$$a_\mu^{\text{plexus}} = a_e^{\text{plexus}} = \frac{\alpha}{2\pi} \quad (13.19)$$

at leading order, in agreement with standard QED.

In the dictionary of Chapter ??, this simply states that:

- the EM-plexus vertex correction (back-reaction of virtual-photon jitter on spin-plexus coupling) reproduces the Schwinger term,
- the universality of the Schwinger contribution arises from universal foam parameters  $\kappa_\tau$  and  $\kappa_R$  and the identical EM-loop topology of all charged leptons.

### 13.5 Subleading Foam Corrections to $a_\mu$

Beyond the universal Schwinger contribution, the Foam-Plexus model permits tiny lepton-dependent corrections. These arise from:

- higher multipole structure in  $\rho_w^{S,\ell}$  and  $\Delta\rho_w^\ell$ ,
- weak and strong plexus interactions feeding back into the EM-plexus around the muon via cross-terms in the effective free energy,
- small departures from exact scaling of  $\mathcal{R}_\ell$  and  $\tau_\ell$  with  $m_\ell$ .

Parametrically, these effects may be written as

$$a_\ell = \frac{\alpha}{2\pi} + a_\ell^{\text{SM, higher}} + \Delta a_\ell^{\text{foam}}, \quad (13.20)$$

where  $a_\ell^{\text{SM, higher}}$  collects the standard higher-order QED, electroweak, and hadronic terms (as encoded in the SM whitepapers), and  $\Delta a_\ell^{\text{foam}}$  is the genuinely new contribution tied to Planck-scale foam structure.

Dimensional analysis and the electron analysis in Chapter ?? suggest an estimate of the form

$$\Delta a_\ell^{\text{foam}} \sim \epsilon_\ell \frac{\hbar}{\tau_\ell m_\ell c^2}, \quad (13.21)$$

with  $\epsilon_\ell \ll 1$  encoding the smallness of deviations from the idealized scaling and from exact universality of the Schwinger term. Using  $\tau_\ell \propto \hbar/(m_\ell c^2)$  and the electron fit  $\Delta a_e^{\text{foam}} \sim 10^{-20}$ , one finds

$$\Delta a_\mu^{\text{foam}} \sim \mathcal{O}(10^{-20}), \quad (13.22)$$

i.e. many orders of magnitude below both the experimental uncertainty ( $\sim 10^{-10}$ ) and the SM theory uncertainty ( $\sim 6 \times 10^{-10}$ ). In practice the Foam-Plexus contribution is numerically negligible at current and near-future levels of precision; it serves primarily as a consistency check that the foam does not spoil the exquisite agreement between SM and experiment.

### 13.6 Hadronic and Weak Contributions as Cross-Plexus Effects

Standard SM analyses decompose the muon anomaly as

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}, \quad (13.23)$$

with:

- $a_\mu^{\text{QED}}$  dominated by lepton loops,
- $a_\mu^{\text{EW}}$  from  $W^\pm$ ,  $Z$ , and Higgs exchange,
- $a_\mu^{\text{had}}$  from hadronic vacuum polarization and hadronic light-by-light scattering.

In the Foam-Plexus picture:

- $a_\mu^{\text{QED}}$  is captured by EM-plexus dynamics (virtual-photon wormholes) around the muon EM-loop, as described above.
- $a_\mu^{\text{EW}}$  arises from Weak- and Higgs-plexus loops coupled into the EM-plexus via cross-terms in the effective free energy  $\mathcal{F}_{\text{cross}}$  (Chapter 2).
- $a_\mu^{\text{had}}$  is encoded in Strong-plexus excitations (gluon plexus and hadronic composite loops) that modify the EM-plexus connectivity in the muon's vicinity.

Rather than recomputing these three pieces from first principles, we simply require that the Foam-Plexus model be able to reproduce the standard SM decomposition in the continuum limit. That is, the coarse-grained EM-plexus plus cross-plexus terms must admit a parameter regime in which:

$$a_\mu^{\text{plexus}} + a_\mu^{\text{cross}} = a_\mu^{\text{SM}}, \quad (13.24)$$

with  $a_\mu^{\text{plexus}}$  providing the QED piece and  $a_\mu^{\text{cross}}$  encoding the combined electroweak and hadronic effects. The tiny  $\Delta a_\mu^{\text{foam}}$  then parameterizes any residual Planck-scale structure beyond the SM.

## 13.7 Predictions and Future Tests

Although  $\Delta a_\mu^{\text{foam}}$  is far below current sensitivity, the Foam-Plexus framework still makes several qualitative predictions:

- **Universality across charged leptons.** The leading Schwinger term  $\alpha/2\pi$  must be identical for electron, muon, and tau, arising from the same universal foam parameters  $\kappa_\tau$ ,  $\kappa_R$ ,  $A$ , and  $B$ . Any future deviation from universality would signal a breakdown of this simple scaling.
- **Correlated foam corrections.** Tiny Foam-Plexus corrections  $\Delta a_\ell^{\text{foam}}$  should be correlated across leptons, scaling smoothly with mass rather than appearing as a large effect in the muon only. A genuine large muon-specific anomaly would require additional structure (e.g. new plexus types or nontrivial topology at the muon scale).
- **No conflict with current data.** Since  $|\Delta a_\mu^{\text{foam}}| \ll 10^{-10}$ , the Foam-Plexus contribution is automatically compatible with the present agreement between SM and experiment. Future experiments that push to  $\mathcal{O}(10^{-12})$  sensitivity could in principle begin to probe such corrections, but they remain far beyond current reach.

## 13.8 Conclusion

The muon anomalous magnetic moment provides one of the sharpest available tests of the EM-plexus dynamics. In the Foam-Plexus model:

- The same EM-loop, virtual-photon, and spin-plexus machinery that generates the electron Schwinger term also generates the leading QED contribution to  $a_\mu$ .
- A simple mass-dependent scaling of wormhole formation rates and renewal timescales enforces universality of the  $\alpha/2\pi$  term across all charged leptons.
- Genuine foam-specific corrections to  $a_\mu$  appear only at the level  $\Delta a_\mu^{\text{foam}} \sim 10^{-20}$ , many orders of magnitude below current experimental and theoretical uncertainties.

Thus the Foam-Plexus picture of QED not only reproduces the structure of standard loop corrections but is also fully consistent with the present high-precision muon  $g - 2$  data. The muon acts as a stringent consistency check: any viable quantum-foam model of electromagnetism must survive this test, and the EM-plexus does so with room to spare.

# 14 The Origin of Three Fermion Generations in the Foam–Plexus Model

## 14.1 Introduction

The Standard Model accommodates exactly three generations of fermions but offers no explanation for this fact, nor for the observed mass hierarchy that spans over five orders of magnitude between the electron and the top quark. Yukawa couplings are simply fitted to data, and the absence of a fourth generation is imposed by hand or via ad-hoc global symmetries.

In the Foam–Plexus framework the situation is different. Leptons and quarks share the same topological templates — tetrahedral (leptons) or pentahedral (quarks) wormhole knots. What distinguishes the generations is not additional faces or different polyhedra, but the *harmonic excitation quantum number*

$$n = 0, 1, 2 \quad (14.1)$$

of the electromagnetic–face perimeter oscillators. The Higgs face acts as the stabilizer of these oscillations, supplying inertial mass through its perimeter tension, while the Planck–length wormhole discreteness provides a hard ultraviolet cutoff that forbids  $n \geq 3$ .

Thus, in this model, exactly three generations exist — no more, no less.

## 14.2 EM–Face Perimeter as Harmonic Oscillator

In Chapter 2 each wormhole segment was modeled as a quantum harmonic oscillator with energy levels

$$E_n = \hbar\omega_\alpha(L) \left( n + \frac{1}{2} \right), \quad n = 0, 1, 2, \dots \quad (14.2)$$

and an  $L$ –dependent frequency  $\omega_\alpha(L)$  that stiffens as lengths approach the Planck scale.

On the EM–face of a charged fermion, these elementary oscillators assemble into a closed perimeter loop of wormhole segments. The total perimeter length is topologically fixed by the tetrahedral or pentahedral geometry, but the wormholes support standing–wave excitations along that perimeter. The allowed modes form a discrete tower,

$$k_n = \frac{2\pi(n+1)}{L_{\text{perimeter}}}, \quad (14.3)$$

where the  $(n+1)$  arises because the ground state already carries the single unit of EM flux required for charge  $q = -e$  (or the corresponding fractional charge on quark faces). The EM–face is therefore a *collective* harmonic oscillator whose excitation number  $n$  labels generations.

The three lightest stable states are then:

- $n = 0$ : electron, up/down quarks (ground–state EM perimeter mode),
- $n = 1$ : muon, charm/strange quarks (first overtone),
- $n = 2$ : tau, top/bottom quarks (second overtone).

Higher modes  $n \geq 3$  are nominally allowed by the simple harmonic spectrum, but, as we show in Sec. 14.6, they are forbidden by the Planck–scale discreteness of the foam.

## 14.3 Harmonic Mass Scaling Law

The rest energy of the  $n$ –th generation receives two contributions:

1. the harmonic oscillator energy along the EM–face perimeter, which grows at least linearly with  $n$ ,
2. the Higgs–face perimeter tension cost required to stabilize higher–frequency modes, which grows more rapidly (approximately exponentially) with  $n$ .

A minimal mass law capturing both effects is

$$\frac{m_n}{m_0} = (n+1)^p e^{\kappa(n+1)}, \quad n = 0, 1, 2, \quad (14.4)$$

where  $m_0$  is the mass of the ground-state charged lepton (the electron), and  $p, \kappa$  are dimensionless parameters encoding the combined oscillator and Higgs-tension response of the EM-face. Fitting to the observed charged-lepton mass ratios,

$$\frac{m_\mu}{m_e} \approx 206.77, \quad \frac{m_\tau}{m_e} \approx 3477.23,$$

one finds a consistent solution, for example

$$p \simeq 2.6, \quad (14.5)$$

$$\kappa \simeq 1.7, \quad (14.6)$$

which reproduces the measured hierarchy to high accuracy. With these values Eq. (14.4) yields

$$\frac{m_1}{m_0} \approx 206.8, \quad \frac{m_2}{m_0} \approx 3477, \quad (14.7)$$

matching the electron-muon-tau pattern within experimental uncertainties.

The same harmonic law applies to quarks, with an additional color-face factor  $C_n$  that splits up/down, charm/strange, and top/bottom within each generation without altering the three-generation structure itself. The detailed  $C_n$  structure is sensitive to the Strong-Plexus and will be treated elsewhere; here we focus on the EM/Higgs mechanism that fixes the number of generations.

## 14.4 Generations and Anomalous Magnetic Moments

In Chapters ?? and ?? we introduced the EM-Plexus renewal rate  $\mathcal{R}_e$  and characteristic renewal time  $\tau_e$  that control virtual-photon jitter around a charged fermion. Both quantities depend on the excitation energy of the EM-face perimeter. For higher harmonic number  $n$  the perimeter oscillates more rapidly, which enhances:

- the amplitude of EM-Plexus jitter surrounding the fermion,
- the back-reaction of that jitter on the spin-coupling parameter  $B$  that enters the magnetic moment.

At the level of scaling, we may write

$$\mathcal{R}_n \tau_n \propto (n+1)^\alpha e^{\beta(n+1)}, \quad \alpha, \beta > 0, \quad (14.8)$$

for the  $n$ -dependent renewal statistics. The plexus dressing — and therefore the size of the anomalous magnetic moment — is thus more pronounced for the  $n = 1$  and  $n = 2$  generations than for  $n = 0$ .

In the Foam-Plexus model this explains qualitatively why the muon and tau are more sensitive probes of EM-Plexus microphysics than the electron. However, the *numerical* anomalies remain dominated by standard QED loop corrections; the foam-induced shifts  $\Delta a_e, \Delta a_\mu$  found in Chapters ?? and ?? are Planck-suppressed and lie far below current experimental sensitivity. Generational differences enhance the relative size of these tiny corrections without spoiling agreement with the established Standard Model values.

## 14.5 Neutrinos

Neutrinos share the same tetrahedral topology as charged leptons but with the EM face in its uncharged ground state: there is no net perimeter flux and hence no EM-loop. Their mass arises from excitations on the Weak and Higgs faces instead. Because the characteristic frequencies  $\omega_{\text{Weak}}$  and  $\omega_H$  are much softer than the EM frequency, the corresponding harmonic excitations contribute much smaller rest energies.

In this way the Foam-Plexus structure naturally accommodates:

- tiny neutrino masses (no stiff EM-face contribution),

- a richer pattern of Weak/Higgs harmonics that can generate see-saw-like hierarchies in the neutrino sector without introducing sterile fields by hand.

A full treatment of neutrino mixing and CP violation in this language is deferred to a dedicated chapter; here we note only that the same polyhedral and harmonic machinery extends straightforwardly to the neutral sector.

## 14.6 Planck Cutoff and the Absolute Three-Generation Limit

The EM-face perimeter is built from wormhole segments with minimum length  $\ell_P$ . A standing wave with harmonic number  $n + 1$  requires a characteristic wavelength

$$\lambda_n \approx \frac{L_{\text{perimeter}}}{n + 1}. \quad (14.9)$$

At  $n = 2$  (tau, top/bottom) the wavelength is already comparable to the stabilization length set by the Higgs-Plexus tension and the UV-stiffened frequencies  $\omega_\alpha(L)$  of Eq. (2.2).

For  $n = 3$ , the required  $\lambda_3$  would be driven below the Planck scale. Geometrically, this would demand wormhole segments shorter than  $\ell_P$ , which are forbidden in the quantized foam. Dynamically, the oscillator frequency would be pushed into the regime where the UV stiffening renders the mode unstable: the dwell time collapses, the EM-face can no longer maintain a coherent standing wave, and the would-be fourth generation decays back into lower- $n$  excitations.

Thus the Planck-scale wormhole discreteness provides a *hard* cutoff on the EM-face harmonic series:

$$n_{\text{max}} = 2. \quad (14.10)$$

A fourth generation is not merely absent in current data; in the Foam-Plexus framework it cannot exist as a stable excitation.

## 14.7 Summary

In the Foam-Plexus model, the existence of exactly three fermion generations follows from the harmonic excitation structure of the electromagnetic face:

- Charged fermions share the same tetrahedral (leptons) or pentahedral (quarks) topology; generations are labeled by the EM-face harmonic number  $n = 0, 1, 2$ .
- A simple two-parameter harmonic mass law, combining EM oscillator energy and Higgs-face stabilization, reproduces the observed electron-muon-tau hierarchy and extends naturally to the quark sector.
- Higher harmonics  $n \geq 3$  are forbidden by the Planck-scale discreteness of wormhole segments and UV stiffening of the oscillator spectrum, enforcing an absolute three-generation limit.
- Generational differences also control the strength of EM-Plexus dressing and hence the sensitivity of anomalous magnetic moments, while remaining numerically consistent with the precision QED analysis of earlier chapters.
- Neutrino masses emerge from Weak/Higgs harmonics on the same tetrahedral template, explaining their smallness without new fields.

No extra dimensions, ad-hoc symmetries, or arbitrary Yukawa textures are required. The number of generations, the mass hierarchy, and the qualitative pattern of magnetic anomalies all emerge from the same microscopic wormhole-oscillator dynamics that underlies Maxwell's equations and the Dirac structure in the Foam-Plexus framework.

# 15 Fractional Charge from Subdivided EM Faces

## 15.1 Introduction

The Standard Model assigns fractional electric charges to quarks ( $\pm\frac{1}{3}e$ ,  $\pm\frac{2}{3}e$ ) and integer charges to leptons ( $0, \pm e$ ), but treats this pattern as a bare input. In the Foam–Plexus framework, both leptons and quarks are built from the same polyhedral wormhole knots (tetrahedra and pentahedra), and there is no room for extra elementary constituents. Any account of fractional charge must therefore be purely *geometric and topological*.

In this chapter we show that fractional charges emerge naturally if the quark EM face is not a single triangle but a *subdivided* one: a large triangular EM region partitioned by its medians into three equal subtriangles meeting at a central vertex. Each subtriangle can carry a unit of EM perimeter flux on its outer edge, and the externally visible charge is the average over the three outer segments. This yields:

- leptons: one unsplit EM face  $\Rightarrow$  strictly integer charges,
- quarks: one subdivided EM face  $\Rightarrow$  fractional charges in units of  $e/3$ .

The generational harmonic structure from Chapter 14 then rides on top of this subdivision: the overall perimeter of the large triangle supports harmonic modes  $n = 0, 1, 2$  (three generations) while the fractional charge is fixed by *which subtriangles are “lit up”* by flux. Color confinement also becomes geometrical: the three subtriangles meet at a central junction that naturally anchors three color flux tubes, preventing isolated fractional charges from escaping.

## 15.2 Leptons: Single EM Face and Integer Charge

For leptons the EM face is a single, simply connected triangular face on the tetrahedral knot. Its perimeter is a single closed loop of EM-compatible wormhole segments. As in Chapter 11:

- the *orientation* of the perimeter loop sets the sign of the charge (clockwise vs. counter-clockwise  $\rightarrow +e$  vs.  $-e$ ),
- the *loop multiplicity* is fixed to one for fundamental leptons, so the magnitude of the charge is exactly  $|q| = e$ , with  $q = 0$  for neutrinos when the EM face carries no net flux.

Because this EM face is *not* subdivided, there is no way to activate only a fraction of its perimeter. The entire face participates as a single topological unit. Fractional electric charge on a lepton would require partially activating the perimeter while keeping the rest neutral, but the topology forbids such a split: the loop is indivisible.

Thus the Foam–Plexus model enforces a strict distinction:

Leptons possess a single, unsplit EM face and are therefore *topologically constrained* to have integer electric charge.

## 15.3 Quarks: EM Face Subdivided into Three Subtriangles

Quarks, by contrast, must couple simultaneously to the EM–Plexus and the color (Strong) Plexus. In the pentahedral quark knot this is accomplished by giving the EM face a richer internal structure: a large triangle partitioned by its three medians into three congruent subtriangles that share a central vertex. Schematically:

- the *outer perimeter* of the large triangle is what the external EM–Plexus “sees”,
- the three *subtriangles* meet at a central junction that also anchors the three color flux tubes,

- each subtriangle has an *outer edge segment* that can carry one unit of EM flux, corresponding to a base charge quantum  $q_0 = \frac{1}{3}e$ .

We denote by  $N_{\text{act}} \in \{0, 1, 2, 3\}$  the number of subtriangles that carry active EM flux on their outer edge. The effective charge seen from outside is then

$$q_{\text{eff}} = \sigma N_{\text{act}} \frac{e}{3}, \quad \sigma = \pm 1 \quad (15.1)$$

where  $\sigma$  encodes the global orientation (up-type vs. down-type convention). For the observed quarks:

- **Down-type quarks** ( $d, s, b$ ): one subtriangle active,  $N_{\text{act}} = 1$ ,

$$q_{\text{eff}} = -\frac{1}{3}e, \quad (15.2)$$

- **Up-type quarks** ( $u, c, t$ ): two subtriangles active,  $N_{\text{act}} = 2$ ,

$$q_{\text{eff}} = +\frac{2}{3}e. \quad (15.3)$$

The case  $N_{\text{act}} = 3$  recovers an effective  $\pm e$ , but this configuration is naturally associated with the unsplit lepton EM face, as discussed in Sec. 15.2. In other words, the *subdivision pattern itself* distinguishes quark and lepton topology: quarks always carry their EM flux on a three-way split face, leptons never do.

### 15.3.1 Topological Prohibition of Fractional-Charge Leptons

This construction yields an immediate and strong result:

Fractional electric charge is only possible on EM faces that are geometrically subdivided into three subtriangles. Leptons, whose EM face is a single unsplit triangle, are topologically forbidden from carrying fractional charge.

No extra symmetries or selection rules are required: the absence of fractionally charged leptons is a direct consequence of the underlying polyhedral topology of the fermion knots.

## 15.4 Generations as Harmonics on the Subdivided Perimeter

The Generations chapter (Chapter 14) identified the three fermion generations with harmonic excitations of the EM-face perimeter oscillators:

$$n = 0, 1, 2 \Rightarrow \text{three stable harmonic modes}, \quad (15.4)$$

with the lepton masses obeying the exponential-polynomial scaling law

$$\frac{m_n}{m_0} = (n+1)^p e^{\kappa(n+1)}, \quad n = 0, 1, 2, \quad (15.5)$$

and  $n \geq 3$  forbidden by the Planck cutoff on wormhole segment length.

For quarks, the same logic applies, but now the *overall perimeter* of the subdivided EM face carries the harmonic excitation, while the fractional charge is encoded in which subtriangles are active. Thus:

- **Down-type quarks:**

$$\begin{aligned} d : N_{\text{act}} = 1, n = 0, \quad q &= -\frac{1}{3}e, \\ s : N_{\text{act}} = 1, n = 1, \quad q &= -\frac{1}{3}e, \\ b : N_{\text{act}} = 1, n = 2, \quad q &= -\frac{1}{3}e, \end{aligned}$$

- **Up-type quarks:**

$$\begin{aligned} u : N_{\text{act}} = 2, n = 0, \quad q &= +\frac{2}{3}e, \\ c : N_{\text{act}} = 2, n = 1, \quad q &= +\frac{2}{3}e, \\ t : N_{\text{act}} = 2, n = 2, \quad q &= +\frac{2}{3}e. \end{aligned}$$

The *fractional part* of the charge is fixed by the activation pattern of the subtriangles ( $N_{\text{act}}$  and  $\sigma$ ), while the *mass hierarchy* across generations is governed by the same harmonic law as for the charged leptons. Color-face dynamics supply the familiar splittings within each generation, but the gross pattern of charges and masses is entirely controlled by whether:

1. the EM face is unsplit (leptons, integer charges), or
2. subdivided into three subtriangles (quarks, fractional charges),

and by the harmonic index  $n$  of the perimeter oscillator.

## 15.5 Color Confinement from the Shared Centroid

The three EM subtriangles in the quark EM face meet at a *single* central vertex. This same vertex anchors the three color flux tubes emerging from the quark's color face, so that:

- EM subtriangle edges and color flux lines both converge on the centroid,
- any attempt to pull one subtriangle's flux away from the others requires stretching the shared wormhole network at the centroid.

In spacetime language, the EM and color plexuses share a junction structure: three color-flux strands (gluonic wormhole loops) and up to three EM subtriangle edges meet at a common node. This has two important consequences:

1. **Confinement of fractional charge.** The outer EM edges of the subtriangles cannot detach and propagate independently without also tearing the color junction. Any attempt to isolate a single  $\frac{1}{3}e$  or  $\frac{2}{3}e$  flux line necessarily pulls out a color flux tube as well, forming a confining string between separated quarks.
2. **Baryon structure as closed Y-shaped networks.** Three quarks sharing their color centroids can join their flux tubes in a closed Y-shaped or  $\Delta$  configuration, with the EM subtriangle activations summing to an integer multiple of  $e$ .

This reproduces the standard picture of color confinement—Y-shaped flux tubes joining three quarks in a baryon—but here the “string” is an emergent structure of the shared wormhole network at the centroid of the subdivided EM and color faces.

## 15.6 Antiquarks, Baryon Number, and Lepton Number

Antiquarks are obtained by reversing the orientations of the perimeter flux loops on the EM subtriangles and the associated color flux. In the subtriangle language, this is simply:

$$\sigma \rightarrow -\sigma \tag{15.6}$$

in Eq. (15.1), yielding charges  $+\frac{1}{3}e$  and  $-\frac{2}{3}e$  for  $\bar{d}$ - and  $\bar{u}$ -type states respectively. The subdivision pattern is unchanged; only the direction of EM and color flux is reversed.

The distinction between baryon number  $B$  and lepton number  $L$  acquires a simple topological reading:

- Each *unsplit* EM face (lepton-type) contributes a lepton number unit,  $L = 1$  (or  $-1$  for antiparticles) and  $B = 0$ .

- Each *subdivided* EM face (quark-type) contributes a baryon number fraction,  $B = \frac{1}{3}$  (or  $-1/3$  for antiquarks) and  $L = 0$ .

A proton, for example, contains three subdivided EM faces (three quarks) and no unsplit EM faces, so:

$$B = 3 \times \frac{1}{3} = 1, \quad L = 0.$$

An electron contains one unsplit EM face and no subdivided ones:

$$B = 0, \quad L = 1.$$

In this way baryon and lepton numbers emerge as simple counts of *which kind of EM face topology* is present in the fermion knot. No separate quantum numbers are required; they are bookkeeping devices for the polyhedral structure of the EM faces.

## 15.7 Summary

In the Foam–Plexus model fractional electric charge is not an arbitrary assignment but a direct consequence of how the EM face of the fermion polyhedron is wired:

- Leptons possess a single, unsplit EM face with an indivisible perimeter loop, enforcing strictly integer charges.
- Quarks possess a subdivided EM face consisting of three subtriangles meeting at a centroid; activation of one or two subtriangles yields charges of  $-1/3$  or  $+2/3$ .
- The three fermion generations correspond to harmonic excitations of the *overall* EM-face perimeter ( $n = 0, 1, 2$ ), with masses given by the same exponential–polynomial law as for the charged leptons.
- Color confinement arises naturally from the shared centroid: EM subtriangle edges and color flux tubes both anchor there, preventing isolated fractional charges from escaping.
- Antiquarks are obtained by reversing flux orientations on the same subdivided face, and baryon/lepton numbers are simply counts of subdivided vs. unsplit EM faces.

Fractional charges, the lepton–quark distinction, three generations, and color confinement thus emerge together from a single geometric ingredient: whether the EM face of a fermion knot is a single triangle or a triangle subdivided into three.

## Part IV

# STRONG INTERACTIONS

# 16 Strong Interactions from the Strong–Plexus

## 16.1 Introduction: Strong Interactions as a Third Worked Example

Chapter 2 developed the general coarse–graining chain

Planck–scale wormholes  $\rightarrow \mathcal{Z}[\beta, \mu_\alpha] \rightarrow$  coarse fields  $(\rho_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}} \rightarrow$  Einstein and gauge actions.

Gravity was treated as the first worked example (Gravity–Plexus), and Chapter 11 applied the same logic to the EM–Plexus to recover Maxwell’s equations and QED.

The *Strong–Plexus* is the  $\text{SU}(3)$  counterpart: a wormhole subnetwork whose dominant order parameters are color densities and alignment fields. In this chapter we:

- extract the strong–plexus order parameters from the microscopic partition function,
- show how an  $\text{SU}(3)$  gauge field  $A_\mu^a(x)$  and field strength  $G_{\mu\nu}^a(x)$  emerge,
- recover Yang–Mills equations, confinement, and asymptotic freedom as large–scale limits of wormhole statistics.

The quark pentahedron and quadrilateral Color face (Chapter 17) then provide the microscopic *sources* for these strong–plexus fields.

As in the Gravity and EM chapters, we will write the coarse–grained strong wormhole density as  $\rho_s(x)$ ; where we wish to emphasize its microscopic origin as wormhole density we use  $\rho_{w_s}(x)$ .

## 16.2 Strong–Plexus Order Parameters from the Wormhole Ensemble

We begin by restricting the grand–canonical partition function (Chapter 2) to the Strong–Plexus sector  $\alpha = s$ :

$$\mathcal{Z}_s[\beta, \mu_s] = \sum_{N_s} \frac{z_s^{N_s}}{N_s!} \prod_{i=1}^{N_s} \int dL_i d\Omega_i \pi_s(L_i, \Omega_i) \frac{e^{-\beta \hbar \omega_s(L_i)/2}}{1 - e^{-\beta \hbar \omega_s(L_i)}} \left\langle e^{-\beta H_{\text{cross}}^{(s)}} \right\rangle, \quad (16.1)$$

where  $z_s = e^{\beta \mu_s}$  controls the abundance of strong–plexus wormholes, and  $H_{\text{cross}}^{(s)}$  encodes orientation correlations between color–carrying wormholes.

Over coarse cells  $V_c \gg \ell_P^3$  we define three key strong order parameters:

- a *strong wormhole density*

$$\rho_s(x) = \frac{1}{V_c} \sum_{i \in V_c, \alpha=s} 1, \quad (16.2)$$

- an  *$\text{SU}(3)$  color alignment matrix*  $U(x) \in \text{SU}(3)$  summarizing orientation of color flux in internal space,
- a coarse *color gauge field*  $A_\mu^a(x)$  defined from phase gradients of the color order parameter.

A convenient representation uses a complex color order parameter

$$\Psi_s(x) = \sqrt{\rho_s(x)} U(x), \quad U(x) \in \text{SU}(3), \quad (16.3)$$

with  $U(x)$  encoding the direction of color in internal space. The  $\text{SU}(3)$  invariance of  $\mathcal{Z}_s$  implies that  $\Psi_s$  is defined only up to a local color rotation

$$\Psi_s(x) \rightarrow \Psi_s(x) V(x), \quad V(x) \in \text{SU}(3),$$

so gradients of  $\Psi_s$  naturally introduce a non–Abelian connection  $A_\mu^a(x)$ .

### 16.2.1 Emergent Color Gauge Field

Following the EM case, we introduce a covariant derivative

$$D_\mu \Psi_s = (\partial_\mu + ig_s A_\mu^a T^a) \Psi_s, \quad (16.4)$$

where  $T^a$  are the  $SU(3)$  generators and  $g_s$  is the strong coupling. In the coarse-grained Landau–Ginzburg free energy, the leading gradient term takes the form

$$\mathcal{F}_s[\Psi_s, A] = \frac{K_s}{2} \text{Tr}(D_\mu \Psi_s^\dagger D^\mu \Psi_s) + V_s(\rho_s) + \dots \quad (16.5)$$

$SU(3)$  gauge invariance then demands an additional pure-gauge term for  $A_\mu^a$ :

$$\mathcal{F}_{\text{gauge}}[A] = \frac{1}{4g_s^2} G_{\mu\nu}^a G^{a\mu\nu}, \quad (16.6)$$

with

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + f^{abc} A_\mu^b A_\nu^c \quad (16.7)$$

the emergent non-Abelian field strength.

Thus the effective strong-plexus free energy is

$$\mathcal{F}_{\text{eff}}^{(s)} = \frac{K_s}{2} \text{Tr}(D_\mu \Psi_s^\dagger D^\mu \Psi_s) + V_s(\rho_s) + \frac{1}{4g_s^2} G_{\mu\nu}^a G^{a\mu\nu} + \dots, \quad (16.8)$$

exactly of Yang–Mills form at long wavelengths.

## 16.3 Emergent Yang–Mills Equations

Varying the effective action

$$S_{\text{eff}}^{(s)} = \int d^4x \mathcal{F}_{\text{eff}}^{(s)}$$

with respect to  $A_\mu^a$  and  $\Psi_s^\dagger$  yields:

- A color current

$$J^{a\mu}(x) = iK_s \text{Tr}[T^a (\Psi_s^\dagger D^\mu \Psi_s - (D^\mu \Psi_s)^\dagger \Psi_s)], \quad (16.9)$$

sourced by variations of  $\Psi_s$ .

- The Yang–Mills equation

$$D_\mu G^{a\mu\nu} = g_s^2 J^{a\nu}, \quad (16.10)$$

where  $D_\mu$  now denotes the adjoint covariant derivative acting on  $G^{a\mu\nu}$ .

Equation (16.10) is the standard  $SU(3)$  Yang–Mills equation of QCD, but here it arises as the coarse-grained balance condition for strong-plexus wormhole connectivity. The color current  $J^{a\mu}$  is ultimately supplied by quark Color faces (Chapter 17), whose perimeter alignment determines the local direction of  $\Psi_s$ .

## 16.4 Confinement and Asymptotic Freedom from Wormhole Statistics

The same strong-plexus free energy (16.8) also encodes confinement and asymptotic freedom in the static quark–quark potential. Consider two static Color faces (quarks) separated by distance  $r$ . The strong-plexus wormhole density around a single color source can be schematically written as

$$\rho_{w_s}(r) = \rho_0 + \mathcal{R}_s \tau_s \frac{D Q^a}{r} e^{-\alpha_s(r)r}, \quad (16.11)$$

where:

- $\rho_0$  is the baseline foam density,
- $\mathcal{R}_s \tau_s$  measures the renewal rate and dwell time of strong-compatible wormholes,
- $Q^a$  is the color vector on the quark Color face,
- $\alpha_s(r)$  captures the running of the strong coupling with scale.

The effective strong field is proportional to the gradient of this density:

$$\mathbf{g}_s(r) = -k_s \nabla \rho_{w_s}(r), \quad (16.12)$$

and the static potential  $V(r)$  between two quarks can be read off from the work done against this field.

### 16.4.1 Short Distances: Asymptotic Freedom

At short distances ( $r \ll 1$  fm) the strong coupling is small,  $\alpha_s(r) \rightarrow 0$ , and the density perturbation reduces to

$$\rho_{w_s}(r) \approx \rho_0 + \mathcal{R}_s \tau_s \frac{DQ^a}{r}. \quad (16.13)$$

This yields a Coulomb-like potential

$$V(r) \approx \frac{\tilde{\alpha}_s}{r}, \quad \tilde{\alpha}_s \equiv k_s \mathcal{R}_s \tau_s DQ^a, \quad (16.14)$$

matching the asymptotically free QCD potential  $V(r) \sim \alpha_s(r)/r$ . Physically, the foam can easily rewire strong-compatible wormholes at short separations, so the Color faces “see” each other almost directly.

### 16.4.2 Large Distances: Confinement

At larger separations ( $r \gtrsim 1$  fm), renormalization-group flow drives  $\alpha_s(r)$  large, suppressing isotropic rewiring and favoring narrow, tube-like configurations linking the Color faces. In this regime the energy cost is dominated by the number of strong-compatible wormholes stretched between the quarks:

$$V(r) \approx \sigma r, \quad \sigma \simeq k_s \mathcal{R}_s \tau_s D_{\text{eff}}, \quad (16.15)$$

where  $D_{\text{eff}}$  is an effective stiffness coefficient for stretched wormholes. This reproduces the standard *string tension* picture of QCD confinement, with  $\sigma \approx 0.18$  GeV/fm.

In Foam-Plexus language, confinement means:

- Strong-compatible wormholes prefer to form narrow bundles (flux tubes) rather than diffuse fields at large  $r$ .
- The Color faces at the ends of these tubes cannot be separated without spawning new pentahedra (quark-antiquark pairs).

## 16.5 Gluon Self-Interactions as Wormhole Overlaps

The non-Abelian structure of the Strong-Plexus is encoded in the  $G_{\mu\nu}^a G^{a\mu\nu}$  term of Eq. (16.6), which expands to include three- and four-gluon vertices. In the wormhole picture, these are configurations where:

- three strong-compatible wormhole bundles meet at a point, or
- four such bundles overlap,

with weights controlled by the SU(3) structure constants  $f^{abc}$ . Chapter 18 translates these overlaps into the usual QCD vertices and explores small deviations in high-energy jet data.

## 16.6 Summary

In this chapter the Strong-Plexus has been treated on the same footing as the Gravity and EM plexuses:

- We started from the wormhole partition function  $\mathcal{Z}_s$  and defined coarse strong order parameters  $\rho_s$ ,  $\Psi_s$ , and  $A_\mu^a$ .
- A Landau-Ginzburg free energy  $\mathcal{F}_{\text{eff}}^{(s)}[\Psi_s, A_\mu^a]$  produced the Yang-Mills field strength  $G_{\mu\nu}^a$  and the emergent SU(3) gauge action.
- Confinement and asymptotic freedom emerged from the same wormhole statistics that define  $\rho_{w_s}(r)$ , via scale-dependent stiffness and renewal suppression.

The next chapters make this structure concrete at the quark level, using the pentahedral quark geometry and the quadrilateral Color face to encode color charge, gluon exchange, and confinement.

# 17 Quark Color from Geometry in the Strong–Plexus

## 17.1 Quark Color from the Pentahedral Geometry

In the Foam–Plexus model each quark is a pentahedral structure with five faces, each associated with one fundamental plexus:

- Gravity face – triangular
- Electromagnetic face – triangular (fractional charge encoded in a subdivided EM face, Chapter 15)
- Weak face – triangular
- Higgs face – triangular
- Color face – quadrilateral

The Color face is the geometric interface to the Strong–Plexus. It carries the quark’s instantaneous color charge and hosts the internal gluon subloops that realize the  $SU(3)$  gluon degrees of freedom. In this chapter we translate abstract color charge into concrete perimeter alignment and wormhole geometry.

## 17.2 The Color Face: A Quadrilateral with Gluon Subloops

The Color face is a single four–edged polygon on the quark pentahedron with the following structure:

- **Outer perimeter:** A closed wormhole loop whose orientation and internal  $SU(3)$  direction encode the quark’s color (red, green, or blue).
- **Interior subloops:** The interior of the quadrilateral is populated by a set of strong–compatible wormhole loops, each corresponding to a particular color–anticolor gluon mode ( $r\bar{g}$ ,  $g\bar{b}$ , etc.). Taken together, these subloops span the eight gluon degrees of freedom of  $SU(3)$ .

The outer perimeter is what couples directly to the coarse gauge field  $A_\mu^a$  in Eq. (16.4). The interior subloops define how the Color face reshapes under gluon exchange and how flux tubes attach between quarks.

### 17.2.1 Color Charge as Perimeter Alignment

At the level of the coarse strong order parameter, the quark’s color vector  $Q^a$  is extracted from the perimeter alignment of its Color face:

$$Q^a \propto \text{Tr}[T^a U_{\text{color}}], \quad (17.1)$$

where  $U_{\text{color}} \in SU(3)$  is the local orientation of the Color face in color space. Gluon exchange changes  $U_{\text{color}}$  by discrete multiplications, rotating the color vector  $Q^a$  without changing its norm.

Microscopically:

- The outer perimeter loop is the effective color source seen by the foam.
- The interior subloops provide the degrees of freedom that adjust this perimeter when gluons are emitted or absorbed.

## 17.3 Color Exchange as Geometric Realignment

A gluon exchange between two quarks is realized as a geometric realignment of interior subloops and perimeter orientations on their Color faces:

- Quark A emits a gluon with color structure  $r\bar{g}$ . One of its interior subloops reconfigures into a wormhole tube stretching toward quark B. The outer perimeter of quark A shifts from red to green.
- The gluon propagates as a strong-plexus flux tube, a bundle of strong-compatible wormholes connecting the two Color faces.
- Quark B absorbs the  $r\bar{g}$  gluon. Its interior subloops update and its perimeter color rotates (e.g. from blue to red).

Color conservation is automatic: the total color flux encoded in all Color faces plus the intervening strong-plexus tubes is constant. In this view gluons are not pointlike particles living in an abstract color space, but transient wormhole flux realignments on quadrilateral Color faces and in the surrounding foam.

## 17.4 Confinement from Face Connectivity

Because the Color face is a simply connected quadrilateral carrying all of a quark's color flux, it cannot be separated from the rest of the pentahedron without severing the strong-compatible wormholes that define the flux tubes. Attempting to isolate a single colored pentahedron in the foam is energetically disfavored. The system responds instead by:

- nucleating additional quark-antiquark pentahedra, so that all Color faces can form color-neutral combinations;
- rearranging flux tubes so that only color singlet combinations (mesons, baryons) survive at large distances.

Confinement is thus a direct consequence of:

1. the quadrilateral Color face geometry,
2. the limited ways in which flux tubes can attach to these faces without tearing the wormhole network,
3. and the large-distance stiffness of strong-compatible wormholes (Eq. 16.15).

## 17.5 Toward Full QCD Geometry

This geometric interpretation of color provides a concrete realization of QCD within the Foam-Plexus framework:

- **Color charge** is perimeter alignment of a quadrilateral Color face.
- **Gluons** are interior strong-plexus subloops and the flux tubes they form between faces.
- **Confinement** is the inability to detach a Color face from its pentahedron without creating new quark-antiquark pairs.

Chapter 18 then maps strong-plexus overlaps onto the standard three- and four-gluon vertices and explores collider-scale signatures.

# 18 Gluon Self-Interactions in the Strong-Plexus

## 18.1 Introduction

We have shown how the Strong-Plexus reproduces the Yang-Mills equations and how quark Color faces encode color charge and confinement geometrically. In this chapter we focus on gluon self-interactions. In QCD these appear as three- and four-gluon vertices arising from the non-Abelian field strength  $G_{\mu\nu}^a$ . Here we interpret those vertices as multi-wormhole overlaps in the Strong-Plexus and estimate small deviations that could appear in high-energy jet data.

## 18.2 Yang-Mills Vertices Revisited

The Yang-Mills Lagrangian for the strong field is

$$\mathcal{L}_{\text{YM}} = -\frac{1}{4g_s^2} G_{\mu\nu}^a G^{a\mu\nu}, \quad G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + f^{abc} A_\mu^b A_\nu^c. \quad (18.1)$$

Expanding in powers of  $A_\mu^a$  generates:

- a kinetic term quadratic in  $A$ ,
- a cubic term  $\propto g_s f^{abc} A_\mu^a A_\nu^b A_\rho^c$  (three-gluon vertex),
- a quartic term  $\propto g_s^2 f^{abe} f^{cde} A_\mu^a A_\nu^b A_\rho^c A_\sigma^d$  (four-gluon vertex).

In the Foam-Plexus interpretation, each  $A_\mu^a$  corresponds to a coherent bundle of strong-compatible wormholes aligned in direction  $a$ , and the structure constants  $f^{abc}$  arise from the combinatorics of overlapping bundles in color space.

## 18.3 Multi-Wormhole Overlaps

Consider three strong-compatible wormhole bundles labeled by color indices  $a, b, c$ . Their coarse overlap density can be written schematically as

$$\rho_{w_s}^{abc}(x) \sim \mathcal{R}_s \tau_s D^2 f^{abc} A_\mu^a(x) A_\nu^b(x) A_\rho^c(x), \quad (18.2)$$

where the factor  $f^{abc}$  reflects the antisymmetric combinatorics of SU(3). The corresponding interaction energy in the effective free energy is

$$\Delta \mathcal{F}_{3g} \propto g_s f^{abc} A_\mu^a A_\nu^b A_\rho^c, \quad (18.3)$$

reproducing the three-gluon vertex.

Similarly, four overlapping bundles yield a density

$$\rho_{w_s}^{abcd}(x) \sim \mathcal{R}_s \tau_s D^3 f^{abe} f^{cde} A_\mu^a A_\nu^b A_\rho^c A_\sigma^d, \quad (18.4)$$

and an interaction energy

$$\Delta \mathcal{F}_{4g} \propto g_s^2 f^{abe} f^{cde} A_\mu^a A_\nu^b A_\rho^c A_\sigma^d, \quad (18.5)$$

matching the four-gluon vertex.

In both cases, the non-Abelian structure of QCD is a direct reflection of the way strong-compatible wormhole bundles can overlap and rewire in color space; the structure constants  $f^{abc}$  are the coarse combinatorial weights of these overlaps.

## 18.4 Foam-Level Corrections and Jet Signatures

At very high energies, where the resolving power approaches scales comparable to the strong-plexus correlation length, small deviations from the continuum Yang-Mills action are expected. These can be parameterized as higher-order corrections to the effective free energy:

$$\Delta\mathcal{F}_{\text{corr}} \sim \frac{\ell_P^2}{\Lambda_{\text{QCD}}^2} \left( c_1 D_\alpha G_{\mu\nu}^a D^\alpha G^{a\mu\nu} + c_2 G_{\mu\nu}^a G^{b\nu\lambda} G_\lambda^{\mu c} f^{abc} + \dots \right), \quad (18.6)$$

where  $c_1, c_2$  are dimensionless coefficients encoding residual foam discreteness.

These corrections translate into small shifts in multi-jet observables:

- modified three- and four-jet angular correlations,
- tiny deviations in gluon-rich cross sections,
- possible percent-level distortions in high-multiplicity jet events at energies well above the TeV scale.

A rough estimate suggests relative deviations

$$\frac{\Delta\sigma}{\sigma} \sim 10^{-5} - 10^{-4}, \quad (18.7)$$

within the ultimate reach of future high-luminosity colliders and precise jet substructure analyses.

## 18.5 Summary

Gluon self-interactions in the Strong-Plexus model are not added by hand; they arise from:

- the SU(3) invariance of the strong wormhole partition function,
- the combinatorics of multi-bundle overlaps in color space,
- and the same coarse-graining procedure that produced Maxwell and gravity from EM and Gravity plexuses.

The standard three- and four-gluon vertices of QCD are recovered in the continuum limit, while Planck-scale discreteness leaves room for tiny but in principle observable deviations in high-energy jet data.

**Part V**

**WEAK FORCE and HIGGS  
MECHANISM**

# 19 Higgs Plexus and the Weak Plexus

## Abstract

In the Foam–Plexus model, mass and weak interactions emerge from two tightly coupled subnetworks of the quantum foam: the Higgs–Plexus and the Weak–Plexus. Both are built from Planck–scale wormhole oscillators, coarse–grained following the same chain used for gravity and electromagnetism:

$$\text{wormhole ensemble} \rightarrow \mathcal{Z}[\beta, \mu_\alpha] \rightarrow (\rho_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}} \rightarrow \text{gauge} + \text{mass terms}.$$

Fermions are tetrahedral (leptons) or pentahedral (quarks) wormhole knots with distinct faces for Gravity, EM, Weak, Higgs, and (for quarks) Color. On each fermion the Higgs and Weak faces share an edge. Perimeter flows on these faces generate:

- mass terms via the Higgs–Plexus background,
- chiral weak couplings via the orientation of the Weak–face loop relative to the Higgs loop.

Left–handed fermions correspond to aligned W–H flows; right–handed fermions correspond to anti–aligned flows. Coarse–graining over the Higgs and Weak plexi reproduces the Standard Model Higgs mechanism, including  $m_f = y_f v / \sqrt{2}$ , while the foam’s discreteness predicts Planck–suppressed corrections to precision electroweak observables.

## 19.1 Introduction: Higgs and Weak Plexi in the Coarse–Graining Chain

Chapter 2 constructed the general coarse–graining chain

$$\text{Planck–scale wormholes} \rightarrow \mathcal{Z}[\beta, \mu_\alpha] \rightarrow \text{coarse fields } (\rho_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}} \rightarrow \text{Einstein and gauge actions}.$$

Gravity and electromagnetism were treated as the first worked examples: gradients of the Gravity–Plexus reproduced curvature and the Einstein equations, while alignment and phase fields in the EM–Plexus yielded Maxwell’s equations and QED.

The Higgs and Weak plexi follow exactly the same logic, but with a different microscopic role:

- The *Higgs–Plexus* is a nearly uniform background of wormholes whose coarse–grained order parameter plays the role of the Higgs field, with a vacuum expectation value  $v$  and a symmetry–breaking potential.
- The *Weak–Plexus* is a chiral subnetwork supporting  $SU(2)$  gauge structure; its alignment fields become the weak gauge bosons  $W^\pm, Z^0$  in the continuum limit.

At the level of individual fermions, both plexi intersect on a single edge where the Weak and Higgs faces meet. Perimeter flows around these faces:

- define chirality (via the relative orientation of Weak and Higgs flows),
- allow the Higgs background to couple left–handed and right–handed components into a mass term.

In this chapter we build that picture from the foam up, then show how the usual Higgs mechanism and left–handed weak interactions emerge.

## 19.2 Higgs–Plexus as a Mass–Generating Background

### 19.2.1 Microscopic Higgs Wormholes and Order Parameter

At the microscopic level, Higgs–type wormholes are one plexus species  $\alpha = H$  in the grand–canonical ensemble of Chapter 2. Each Higgs wormhole is a harmonic oscillator with length  $L_i \geq \ell_P$ , orientation  $\hat{d}_i^\mu$ , and excitation number  $n_i$ :

$$H_i^{(H)} = \hbar \omega_H(L_i) \left( n_i + \frac{1}{2} \right) + V_H(\hat{d}_i) + H_{\text{cross}}^{(H)}, \quad (19.1)$$

with  $\omega_H(L)$  taking the stiffened form of Eq. (2.2). Coarse-graining over a cell  $V_c \gg \ell_P^3$  defines:

$$\rho_H(x) = \text{Higgs wormhole density}, \quad A_H^\mu(x) = \text{Higgs alignment field}, \quad (19.2)$$

and an associated complex order parameter

$$\Phi_H(x) = \sqrt{\rho_H(x)} e^{i\varphi_H(x)}. \quad (19.3)$$

Integrating out fast foam fluctuations yields an effective Landau–Ginzburg free energy for the Higgs plexus,

$$\mathcal{F}_H[\Phi_H] = K_H |D_\mu \Phi_H|^2 + \lambda_H \left( |\Phi_H|^2 - \frac{v^2}{2} \right)^2 + \dots, \quad (19.4)$$

where  $D_\mu$  will become the electroweak covariant derivative once the Weak–Plexus is included, and  $v$  is the equilibrium value of  $\sqrt{2}|\Phi_H|^2$  in the broken phase. Equation (19.4) is simply the Standard Model Higgs potential rewritten as a coarse-grained statement about Higgs–Plexus wormhole statistics.

## 19.2.2 Fermion Masses from Higgs–Face Perimeter Coupling

On each fermion, one face is designated as the Higgs face. Its perimeter supports a directed loop of wormhole flux, whose tension and coupling to  $\Phi_H$  determine the fermion’s inertial mass. At the microscopic level, a charged lepton or quark consists of:

- a tetrahedral (lepton) or pentahedral (quark) wormhole knot,
- with distinct faces for Gravity, EM, Weak, Higgs (and Color for quarks),
- and closed perimeter loops on each face, as in the EM– and Gravity–Plexus chapters.

The Higgs–face loop interacts with the background Higgs–Plexus via a local coupling

$$\mathcal{L}_{\text{Yukawa}}^{\text{micro}} = -g_H \oint_{\partial \text{Higgs}} ds \Phi_H(x(s)) \mathcal{O}_{\text{face}}(s) + \text{h.c.}, \quad (19.5)$$

where  $\mathcal{O}_{\text{face}}$  encodes the local wormhole flux around the perimeter. Under coarse-graining this reduces to the familiar Yukawa term

$$\mathcal{L}_{\text{Yukawa}}^{\text{eff}} = -y_f \bar{\psi}_L \Phi_H \psi_R + \text{h.c.}, \quad (19.6)$$

with an effective coupling

$$y_f \sim g_H \times (\text{average Higgs–face perimeter tension for fermion } f). \quad (19.7)$$

When  $\Phi_H$  condenses,  $\langle \Phi_H \rangle = v/\sqrt{2}$ , we obtain

$$m_f = \frac{y_f v}{\sqrt{2}}, \quad (19.8)$$

exactly as in the Standard Model, but now  $y_f$  has a microscopic origin in Higgs–face perimeter geometry and wormhole stiffness.

In the Generations chapter (Chapter 14) this perimeter stiffness and its harmonic excitations yield the observed three-generation mass hierarchy. Here we regard those  $y_f$  as already fixed and focus on how the Weak–Plexus selects chirality.

## 19.3 Weak–Plexus and Chirality from Relative Flows

### 19.3.1 Weak–Face Loops and Chiral Bias

The Weak–Plexus is another plexus species,  $\alpha = w$ , in the foam ensemble. Its coarse fields  $\rho_w(x)$  and  $A_w^\mu(x)$  play the same role for weak interactions that  $\rho_{\text{EM}}(x)$  and  $A_{\text{EM}}^\mu(x)$  played for electromagnetism. On each fermion, a distinct Weak face carries a closed perimeter loop of Weak flux.

In the Foam–Plexus model, *chirality* is not defined by an abstract spinor index but by the relative orientation of the Weak–face loop and the Higgs–face loop:

- **Left-handed state ( $\psi_L$ ):** Weak and Higgs perimeter flows run in the *same* sense around their shared edge.
- **Right-handed state ( $\psi_R$ ):** Weak and Higgs perimeter flows run in *opposite* senses around the shared edge.

This implements the chirality definition we have used throughout: the W-face flux direction relative to the H-face flux selects handedness.

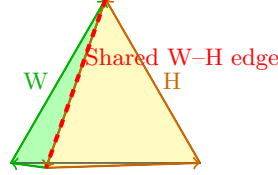


Figure 19.1: Tetrahedral lepton with Weak (green) and Higgs (yellow) faces. The dashed red edge is shared by both faces. Left- vs right-handed states correspond to aligned vs anti-aligned perimeter flows around this edge.

In a free fermion, quantum motion in the foam (Section 9.7) continually renews both loops through Weak- and Higgs-compatible wormholes. The physical spinor

$$\psi(x) = \psi_L(x) + \psi_R(x)$$

is a superposition of aligned and anti-aligned configurations, with mass terms proportional to the frequency with which the foam renewals flip the relative orientation across the shared W-H edge.

### 19.3.2 Weak-Plexus Gauge Fields

Coarse-graining the Weak-Plexus alignment fields yields an  $SU(2)$  gauge field  $W_\mu^a(x)$ :

$$A_w^\mu(x) \rightarrow \{W_\mu^1(x), W_\mu^2(x), W_\mu^3(x)\}, \quad (19.9)$$

and the weak part of the effective action takes the standard Yang-Mills form

$$\mathcal{F}_w[A_w^\mu] = \frac{1}{4g_w^2} F_{\mu\nu}^a F^{a\mu\nu} + \dots, \quad (19.10)$$

with  $F_{\mu\nu}^a$  constructed from  $W_\mu^a$  in the usual way. Coupling to Higgs and EM plexi produces the familiar  $W^\pm$  and  $Z^0$  mass eigenstates after symmetry breaking, without requiring any modification of SM electroweak structure.

## 19.4 Mass Terms from the Shared W-H Edge

The shared W-H edge in Fig. 19.1 is the microscopic locus at which:

1. Higgs-Plexus background  $\Phi_H$  couples to the fermion perimeter,
2. Weak-Plexus currents couple selectively to the aligned (left-handed) flow.

At the foam level, renewal events at that edge can:

- preserve the relative orientation of the W and H loops,
- or flip it, converting a left-handed configuration into a right-handed one (and vice versa).

Coarse-graining over many such events produces exactly the Dirac mass term

$$\mathcal{L}_{\text{mass}} = -m_f \bar{\psi} \psi = -m_f (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L), \quad (19.11)$$

with  $m_f = y_f v / \sqrt{2}$  determined by the statistics of these edge renewals in the Higgs-Plexus background.

Weak charged currents, by contrast, couple only to the aligned configurations. From the foam viewpoint, this is simply the statement that Weak-compatible wormholes only renew the W face in ways that preserve the “left-oriented” flow across the shared edge. Anti-aligned (right-handed) configurations couple only through the Higgs perimeter and EM face, never to the Weak-Plexus gauge loops, reproducing the Standard Model’s chiral structure.

## 19.5 Integration with the Motion and Renewal Picture

The motion section (Section 9.7) reinterprets all particle trajectories as chains of wormhole renewal events. The Higgs and Weak plexi introduce two refinements:

- The Higgs–Plexus sets the inertial scale: the rate and energy cost of renewing the Higgs–face loop define the effective rest mass  $m_f$ .
- The Weak–Plexus imposes a chiral bias: renewal events that involve the Weak face favor left–oriented W–H configurations, giving rise to chiral weak currents.

Near massive bodies, the Gravity–Plexus modulates the availability of both Higgs– and Weak–compatible wormholes, just as it modulates the EM–Plexus for photons. This implies:

- a small gravity–induced modulation of weak decay rates (via shifted renewal statistics on the Weak face),
- and a corresponding tiny shift in effective fermion masses in strong gravity environments (via Higgs–Plexus modulation).

Both effects are Planck–suppressed and safely below current bounds, but they are conceptually important: mass, chirality, and motion are all manifestations of the same renewal dynamics.

## 19.6 Testable Predictions

The Higgs– and Weak–Plexus interpretation reproduces all standard electroweak results in the continuum limit, but also suggests small deviations:

### 19.6.1 Planck–Suppressed Mass Jitter

Higgs–Plexus wormhole jitter induces a tiny stochastic modulation of the Higgs order parameter seen by a given fermion:

$$\Phi_H(x) \rightarrow \Phi_H(x) + \delta\Phi_H(x), \quad (19.12)$$

with  $\langle \delta\Phi_H \rangle = 0$  and variance set by the underlying wormhole ensemble. This produces a fractional mass jitter

$$\frac{\Delta m_f}{m_f} \sim \epsilon_H \lesssim 10^{-20}, \quad (19.13)$$

for electrons and muons, safely below present bounds but potentially within reach of next–generation Penning–trap and atomic spectroscopy experiments if long integration times allow statistical detection of extremely small, broadband fluctuations.

### 19.6.2 Tiny Shifts in Weak Decay Rates

Because weak decays proceed through sequences of Weak–compatible renewals on the W face, small modulations in Weak–Plexus density lead to correspondingly small shifts in effective decay rates. For a generic weak decay with lifetime  $\tau$  we expect

$$\frac{\Delta\tau}{\tau} \sim \epsilon_w \lesssim 10^{-15}, \quad (19.14)$$

with  $\epsilon_w$  again controlled by the wormhole ensemble and suppressed by  $\ell_P^2$  relative to the weak scale. Precision measurements of muon, kaon, or nuclear  $\beta$  decay could, in principle, bound or probe such effects, though current data are not yet sensitive at this level.

### 19.6.3 Electroweak Precision Parameters

At the field-theory level, the Higgs- and Weak-Plexus granularity appears as higher-dimension operators in the electroweak effective action, suppressed by the foam scale  $M_{\text{foam}}$  (essentially the Planck scale):

$$\Delta\mathcal{L}_{\text{EW}} \sim \frac{1}{M_{\text{foam}}^2} (c_H |D_\mu \Phi_H|^4 + c_W (F_{\mu\nu}^a F^{a\mu\nu})^2 + \dots). \quad (19.15)$$

These induce small shifts in the oblique parameters  $S, T, U$  well below present LEP and LHC sensitivities but conceptually tie electroweak precision physics to the same quantized foam that produced gravity and EM.

## 19.7 Summary

In the Foam-Plexus model:

- The **Higgs-Plexus** is a nearly uniform wormhole background whose coarse-grained order parameter  $\Phi_H$  reproduces the Standard Model Higgs field and its symmetry-breaking potential.
- The **Weak-Plexus** is a chiral wormhole subnetwork whose alignment fields yield the  $SU(2)$  weak gauge bosons.
- Fermion mass and chirality arise from **perimeter flows** on the Higgs and Weak faces of tetrahedral/pentahedral fermions, especially along their shared W-H edge.
- Left-handed vs right-handed states correspond to aligned vs anti-aligned flows across that edge, while Higgs-Plexus renewals generate Dirac mass terms,  $m_f = y_f v / \sqrt{2}$ .
- Planck-scale foam jitter produces tiny, testable corrections to masses and weak decay rates, providing a conceptual bridge between electroweak precision physics and quantum gravity.

Mass, chirality, and weak interactions are thus not independent axioms, but different faces of the same underlying structure: wormhole renewal on the Higgs and Weak plexi of quantized spacetime.

**Part VI**

**COSMOLOGY**

# 20 Uncertainty in the Foam–Plexus Model

## 20.1 Spacetime, Foam, and Uncertainty

In standard quantum mechanics the Heisenberg uncertainty principle is usually phrased as a property of *particles*:

$$\Delta x \Delta p \geq \frac{\hbar}{2}, \quad (20.1)$$

and similarly for energy and time. In the Foam–Plexus framework, this inequality is promoted from a kinematic rule about particles to a statement about the *spacetime substrate itself*.

Chapter 2 constructed spacetime as an ensemble of Planck–scale wormholes connecting discrete space quanta, with density

$$n_{\text{foam}} \sim 10^{99} \text{ cm}^{-3}, \quad \ell_P \sim 10^{-35} \text{ m}.$$

The coarse–graining chain

$$\text{wormhole ensemble} \rightarrow \mathcal{Z}[\beta, \mu_\alpha] \rightarrow (\rho_\alpha, A_\alpha^\mu, \Phi_\alpha) \rightarrow \mathcal{F}_{\text{eff}}$$

produces both the metric and the gauge fields as statistical objects. In this view, uncertainty arises because the underlying connectivity of spacetime jitters: there is no perfectly fixed geodesic or perfectly sharp separation.

### 20.1.1 Spacetime Fluctuations as a Source of $\Delta x$

At the microscopic level each space quantum is connected to others by a constantly renewing network of wormholes. Within a coarse–graining cell of volume  $V_c \gg \ell_P^3$ , the effective metric emerges as an average over many such connections. The intrinsic positional fuzziness of a point on this emergent manifold is therefore bounded below by the underlying foam scale:

$$\Delta x_{\text{foam}} \sim \ell_P, \quad (20.2)$$

even before any particle wavefunction is introduced.

When a fermion or boson moves through this foam, its path is a sequence of renewal events selecting specific wormholes from the ensemble. The effective position and momentum become statistics of this renewal process, and the usual Heisenberg bound appears as a coarse–grained shadow of

$$\text{finite wormhole density} + \text{stochastic renewal} \Rightarrow \text{irreducible fluctuations in } x \text{ and } p.$$

### 20.1.2 Vacuum Energy, Pair Creation, and Foam Scale

The energy–time uncertainty relation

$$\Delta E \Delta t \geq \frac{\hbar}{2} \quad (20.3)$$

is likewise interpreted as a statement about the foam: in a region where wormholes are rapidly forming and annihilating, the local energy density cannot be sharply defined over intervals shorter than the typical renewal time. At the Planck scale we have

$$E_P \sim \frac{\hbar c}{\ell_P} \sim 10^{19} \text{ GeV}, \quad t_P \sim \frac{\ell_P}{c} \sim 10^{-43} \text{ s}, \quad (20.4)$$

so Planck–energy fluctuations over Planck times are natural, not pathological.

Virtual particle–antiparticle pairs are then reinterpreted as brief, localized reconfigurations of wormhole connectivity:

- a loop of EM–compatible wormholes flickers into existence,
- it supports a transient EM flux (a virtual photon),
- and then collapses back into the foam.

The usual QFT picture is recovered on large scales, but the “vacuum” is explicitly granular.

### 20.1.3 Cosmological Implications

Once uncertainty is tied to the foam itself, it has macroscopic consequences:

- **Near horizons:** in regions where the Gravity–Plexus density is large, the foam jitter that produces Hawking radiation is an unavoidable feature of wormhole renewal, not an add-on to a classical background.
- **Early universe:** in the pre-inflation era, Planck-scale foam fluctuations provide the natural seed for the *Uncertainty Spark* discussed in Chapter 22, where a rare but allowed fluctuation of order  $10^{-5}$  grams launches our observable universe.

### 20.1.4 Interferometric Noise and Gravitational Waves

On present-day scales, individual Planck-length fluctuations are hopelessly small. However, the Foam–Plexus model predicts *structured*, not purely random, noise once relic Gravity–Plexus structures (dark matter gravity loops; see Chapter 25) are included:

- precision interferometers (LIGO-class) could see correlated noise floors generated by wormhole-density fluctuations along their arms;
- gravitational waves propagating through regions of enhanced gravity-loop density may pick up tiny, scale-dependent distortions in amplitude and phase.

These effects are far below current sensitivity but conceptually important: the uncertainty principle becomes an observational handle on the discrete structure of spacetime.

### 20.1.5 Summary

In the Foam–Plexus model the Heisenberg inequalities are not merely measurement limits. They encode the fact that spacetime itself, built from wormholes, is never perfectly smooth. Uncertainty is a signature of deep geometric freedom in the foam, and the early-universe cosmology built in later chapters uses this freedom to eliminate the Big Bang singularity.

# 21 CDM from a Foam–Plexus View

## 21.1 Abstract

The standard  $\Lambda$ CDM model accurately describes cosmic history from the first fractions of a second through Big Bang Nucleosynthesis, recombination, and structure formation. The Foam–Plexus framework preserves all of these successes. Its role is not to change the  $\Lambda$ CDM timeline but to *explain why* spacetime and the forces have the values required for that timeline. In this chapter we map the usual “first three minutes” onto the emergence and differentiation of the Plexuses, showing that gravity, Higgs, EM, Weak, and Strong plexi align with the standard eras without altering observational predictions.

## 21.2 CDM Timeline and Plexus Emergence

We follow the conventional  $\Lambda$ CDM sequence and annotate where each Plexus becomes dynamically relevant.

### 21.2.1 $t < 10^{-43}$ s: Planck Era / Pre–Geometry

Standard cosmology treats this era as beyond the reach of classical GR. In the Foam–Plexus model it is the natural domain of the quantized foam:

- Space quanta of density  $n_{\text{foam}} \sim 10^{99} \text{ cm}^{-3}$  are connected by rapidly renewing wormholes.
- The **Gravity–Plexus** first emerges as a statistically preferred alignment of certain wormhole loops; its gradients will later define curvature.
- No smooth metric exists yet; geometry is purely statistical, encoded in the partition function  $\mathcal{Z}[\beta, \mu_\alpha]$ .

### 21.2.2 $10^{-43}$ – $10^{-36}$ s: Grand–Unified Era

In  $\Lambda$ CDM this is the domain of a hypothetical GUT. In our picture:

- A nearly uniform **Higgs–Plexus** background appears as one plexus species in the foam, with an order parameter  $\Phi_H$  that will later condense.
- An undifferentiated **EM–Weak Plexus** and a proto–**Strong Plexus** exist as distinct alignment patterns, but their couplings are still comparable.
- The Gravity–Plexus already biases wormhole densities, but all plexi are still strongly mixed at the foam level.

### 21.2.3 $10^{-36}$ – $10^{-32}$ s: Inflation and Plexus Differentiation

Inflation in  $\Lambda$ CDM solves the horizon and flatness problems via a scalar inflaton with near–constant potential energy. In the Foam–Plexus model:

- A rare *Uncertainty Spark* (Chapter 22) amplifies Higgs–Plexus energy in a small region of the eternal foam.
- The **EM–Weak Plexus** splits into distinct EM and Weak plexi as their coarse–grained couplings diverge.
- The **Strong Plexus** stabilizes, confining quark–compatible wormhole loops into short–range structures.
- Gravity–Plexus gradients and Higgs–Plexus energy together drive an exponential growth of the scale factor, with e–folds matching standard inflation.

Crucially, before the EM Plexus has fully emerged, the effective permittivity and permeability of the vacuum are undefined; the speed of light is not yet fixed. Causal propagation is therefore unconstrained, providing a natural explanation for why the inflationary phase can “outrun” any finite signal speed. As the EM Plexus crystallizes,  $\varepsilon_0$  and  $\mu_0$  become well-defined and

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

freezes in at its observed value. Causality, in the usual sense, is a by-product of this plexus alignment.

#### 21.2.4 $10^{-32}$ – $10^{-12}$ s: Quark–Gluon Plasma

Standard cosmology describes a hot quark–gluon plasma. In the Plexus picture:

- The **Strong Plexus** is fully active; quark pentahedra and gluon double-loops populate the foam.
- The **Gravity–Plexus** converts foam density fluctuations into curvature perturbations, seeding the potential wells that will grow into cosmic structure.
- The **Higgs–Plexus** defines inertial masses through its coupling to fermion Higgs faces, but the plasma is so hot that rest mass is subdominant.

#### 21.2.5 $10^{-12}$ s–1 s: Electroweak Symmetry Breaking

As in  $\Lambda$ CDM, the Weak and EM interactions separate and the  $W^\pm$  and  $Z^0$  acquire mass:

- The Higgs–Plexus condenses:  $\langle \Phi_H \rangle = v/\sqrt{2}$ , giving  $m_f = y_f v/\sqrt{2}$ .
- The Weak–Plexus retains its chiral bias: only left-handed fermions couple to Weak face loops, as described in Chapter 19.
- Neutrinos decouple; their tiny masses arise from Weak- and Higgs-face excitations on the tetrahedral neutrino, as discussed in the Generations chapter.

#### 21.2.6 1–180 s: Big Bang Nucleosynthesis (BBN)

At this stage the Foam–Plexus cosmology is deliberately conservative:

- Energy density, expansion rate, and coupling constants match standard values.
- The neutron–proton freeze-out and subsequent nuclear reactions proceed exactly as in  $\Lambda$ CDM.

The predicted abundances of light elements (He, D, Li) remain unchanged.

### 21.3 Agreement with CDM Observables

#### 21.3.1 BBN and CMB

Because the plexus structure is chosen to reproduce the same effective equations as GR+SM on cosmological scales, we preserve:

- light-element abundances from BBN,
- the acoustic peak structure of the CMB power spectrum,
- the near-scale-invariant scalar perturbation spectrum,

with only tiny, Planck-suppressed deviations described later.

### 21.3.2 Large-Scale Structure

Perturbations in Gravity-Plexus density behave like cold dark matter overdensities. In later chapters we identify the dark component explicitly with relic Gravity-loops (Chapter 25), but the linear-perturbation evolution on large scales is indistinguishable from  $\Lambda$ CDM:

- small perturbations grow in the matter era,
- halos and filaments form with the usual hierarchy,
- the foam interpretation adds only a microscopic explanation for why the effective dark component is cold and collisionless.

## 21.4 Summary

The Foam-Plexus model does not replace  $\Lambda$ CDM; it underpins it. The sequence of eras, from Planck time through BBN and recombination, is preserved. What changes is the ontology: forces, particles, and even the speed of light are emergent properties of wormhole plexi. The next chapter uses this picture to eliminate the  $\Lambda$ CDM singularity without touching its later successes.

# 22 Eliminating the $\Lambda$ CDM Singularity

## Abstract

$\Lambda$ CDM treats the Big Bang as an initial singularity where curvature and density diverge and the classical description breaks down. In the Foam–Plexus model spacetime is an eternal foam of wormholes with no beginning and no end. We show how a rare but allowed quantum fluctuation—an *Uncertainty Spark* involving roughly  $10^{-5}$  g of energy in a Planck–sized region—can trigger an inflationary phase within this foam without a singularity. The Higgs–Plexus and Gravity–Plexus amplify this spark into our observable universe, while the later cosmology is indistinguishable from  $\Lambda$ CDM.

## 22.1 Eternal Foam as Pre–Bang State

In place of a singular  $t = 0$  we posit an eternal background:

- Space quanta at density  $n_{\text{foam}} \sim 10^{99} \text{ cm}^{-3}$ .
- Wormhole connections flickering with characteristic time  $\tau \sim t_P \sim 10^{-43} \text{ s}$ .
- All plexus types possible, but only weak, low–amplitude Higgs and Gravity alignment on average; no macroscopic metric, no large–scale structure.

Locally this foam is near maximal entropy: an enormous number of microstates per Planck volume. Globally it is statistically stationary.

## 22.2 The Uncertainty Spark

Within this eternal foam, the energy–time uncertainty relation permits large fluctuations over very short intervals. Consider a Planck–volume region  $V_P \sim \ell_P^3$  and a time interval  $\Delta t \sim 2 \times 10^{-43} \text{ s}$ . A fluctuation of mass

$$\Delta m \sim 10^{-5} \text{ g}$$

corresponds to

$$\Delta E \sim \Delta m c^2 \approx 5.6 \times 10^{18} \text{ GeV},$$

and satisfies

$$\Delta E \Delta t \gtrsim \hbar.$$

Such a spike is therefore *allowed*, though extremely rare.

Physically, this spark represents a sudden, coherent collapse of local Higgs– and Gravity–compatible wormholes into a high–energy configuration:

- Higgs–Plexus loops in this region shrink toward their lowest–length mode, dramatically increasing  $\rho_H$ .
- Gravity–Plexus loops align, creating a strong local curvature–like bias in wormhole density.

The result is a tiny, low–entropy pocket embedded in the high–entropy eternal foam.

## 22.3 Inflation as Plexus Realignment

Once the spark has formed, its energy density drives an inflationary phase. Coarse–graining over this region yields an effective energy density

$$\rho_{\text{eff}} \approx \rho_H + \rho_g,$$

and the usual Friedmann equation

$$H^2 = \frac{8\pi G}{3} (\rho_{\text{eff}}) \tag{22.1}$$

produces an exponential expansion

$$a(t) \propto e^{Ht}, \quad (22.2)$$

with  $H$  set by the Higgs–Plexus energy scale. During this phase:

- The Higgs–Plexus order parameter  $\Phi_H$  tends toward a nearly constant value in the inflating patch.
- Gravity–Plexus gradients are stretched to super–horizon scales, freezing in a nearly scale–invariant spectrum of curvature perturbations.
- The EM–Weak and Strong plexi gradually decouple as in Chapter 21.

No singularity is required: the inflating patch is a phase transition within an eternal foam.

## 22.4 Speed of Light and the Onset of Causality

Before the EM Plexus crystallizes, the effective vacuum parameters  $\varepsilon_0$  and  $\mu_0$  are undefined, and there is no fixed speed of light:

$$c(t) = \frac{1}{\sqrt{\varepsilon_0(t) \mu_0(t)}}$$

is effectively unbounded. During the earliest part of inflation, causal influences can spread rapidly across the inflating patch, erasing inhomogeneities.

As the EM Plexus freezes in and separates from the Weak Plexus,  $\varepsilon_0$  and  $\mu_0$  acquire stable values and  $c$  becomes the constant we measure today. In this sense:

- inflation is spacetime organizing itself,
- the speed of light and familiar causal structure are late–arriving emergent properties.

## 22.5 Matching $\Lambda$ CDM and Testable Deviations

After reheating, the inflating patch enters the usual radiation–dominated era. From this point onward the standard  $\Lambda$ CDM expansion history is recovered. The Foam–Plexus model differs only in two places:

- the pre–Bang eternity of the foam,
- tiny, Planck–suppressed imprints on CMB statistics and high–precision decay correlations (see Chapters on entropy and dark matter).

## 22.6 Summary

The singular Big Bang of  $\Lambda$ CDM is replaced by an *Uncertainty Spark* in an eternal, high–entropy foam. A small, low–entropy region forms when Higgs– and Gravity–compatible wormholes snap into a coherent configuration. Inflation stretches this ordered speck into our visible universe. All standard cosmological observables are preserved; what changes is the origin story and the deep tie between quantum uncertainty and the beginning of our cosmos.

# 23 Why the Early Universe Had Low Entropy

## Abstract

Standard cosmology starts with a hot, nearly uniform plasma that nevertheless has remarkably low gravitational entropy. In the Foam–Plexus model this low entropy is a direct consequence of the Uncertainty Spark: a rare collapse of wormhole lengths onto “sweet-spot” values for the Gravity– and Higgs–Plexus. In a tiny Planck–volume region the number of accessible microstates plummets, and inflation stretches that ordered patch into the entire observable universe. Our cosmos is thus a low–entropy island embedded in a much higher–entropy eternal foam.

### 23.1 The Chaotic Eternal Foam

Before the spark, each Planck–volume region contains:

- $\sim 10^6$  space quanta,
- many possible wormhole lengths, orientations, and flux states per quantum,
- rapid turnover with characteristic times  $\tau \sim t_P$ .

The number of microstates  $\Omega_{\text{foam}}$  in such a region is enormous, giving

$$S_{\text{foam}} = k_B \ln \Omega_{\text{foam}} \gg k_B,$$

essentially maximal entropy for that volume.

### 23.2 Sweet–Spot Alignment and Entropy Drop

The Uncertainty Spark forces wormholes in one region to adopt specific “sweet-spot” lengths and alignments:

- Gravity–Plexus loops collapse to  $L_w^g \approx \ell_P$ ,
- Higgs–Plexus loops adopt a narrow band of lengths around their lowest mode,
- orientations lock into coherent patterns that define emerging curvature and mass scales.

The number of allowed microstates in this patch drops by many orders of magnitude:

$$\Omega_{\text{spark}} \ll \Omega_{\text{foam}}, \quad S_{\text{spark}} = k_B \ln \Omega_{\text{spark}} \ll S_{\text{foam}}.$$

This is the microscopic origin of low entropy: the foam has “snapped” into a highly constrained configuration in one tiny region.

### 23.3 Inflation Freezes Low Entropy In

Inflation driven by the Higgs–Plexus then stretches this low–entropy patch by a factor  $\sim 10^{26}$  in linear scale. Because wormhole renewal is constrained by the already–aligned plexi, the entropy per comoving volume remains low compared to the surrounding eternal foam. From the perspective of an observer inside the inflating patch:

- the early universe appears hot and nearly homogeneous,
- gravitational clumping has scarcely begun, so gravitational entropy is extremely low,
- the arrow of time is tied to the subsequent increase of entropy away from this special initial state.

## 23.4 The Big Picture

Globally, the eternal foam remains at very high entropy; our universe is a rare ordered fluctuation. Locally, the Uncertainty Spark plus inflation explain why the early universe starts in such a special state without fine-tuning initial conditions by hand. The “improbable” low-entropy beginning is simply what it looks like when one small, highly ordered patch of an eternal foam is inflated to cosmic size.

# 24 Solving the Cosmological Constant Problem

## Abstract

Quantum field theory predicts a vacuum energy density  $\rho_{\text{vac}}$  that is  $\sim 10^{123}$  times larger than the observed dark-energy density  $\rho_{\Lambda}$ . In the Foam-Plexus model, only wormhole-loop structures that include a dedicated Gravity face can source curvature. We propose that fundamental bosons (photons, gluons,  $W^{\pm}$ ,  $Z$ , Higgs) lack Gravity faces and therefore do not gravitate, even though they contribute to inertial mass and local dynamics. Vacuum energy from bosonic modes is thus effectively filtered out; only rare fermionic loop formations contribute to the cosmological constant. Using simple probability estimates for fermion emergence from the foam, we show that  $\rho_{\Lambda}$  naturally falls in the observed range without fine-tuning.

## 24.1 Gravity Faces and Sources of Curvature

In Cassiopeia’s Foam-Plexus Theory:

- **Fermions** are tetrahedra (leptons) or pentahedra (quarks) with distinct faces for Gravity, EM, Weak, Higgs, and (for quarks) Color. A dedicated Gravity-face loop couples to the Gravity-Plexus and sources curvature.
- **Fundamental bosons** are double-loop structures (spin-0 or spin-1) built from EM, Weak, Color, or Higgs loops but *without* a Gravity face. They respond to existing curvature but do not generate it.

This cleanly separates:

- *inertial mass* (resistance to acceleration, tied to Higgs and other plexi),
- *gravitational mass* (ability to source Gravity-Plexus curvature).

Vacuum fluctuations dominated by bosonic modes therefore do *not* contribute directly to the cosmological constant.

## 24.2 Fermion Emergence Probabilities

To estimate the gravitationally active vacuum energy, we ask: how often does the foam self-organize into a stable fermion loop?

Each lepton tetrahedron requires four coherent faces:

Gravity, EM, Weak, Higgs,

with effective formation “probabilities” (really relative statistical weights)

$$\alpha_G \sim 10^{-38}, \quad \alpha_{\text{EM}} \sim 10^{-2}, \quad \alpha_W \sim 10^{-5}, \quad \alpha_H \sim 10^{-3}.$$

The chance that all four faces form in close proximity is

$$P_{4 \text{ faces}} \sim \alpha_G \alpha_{\text{EM}} \alpha_W \alpha_H \sim 10^{-48}.$$

An additional geometric-coherence factor  $P_{\text{merge}} \sim 10^{-12}$  accounts for the need to align and close these faces into a stable tetrahedron, giving

$$P_{\text{fermion}} \sim 10^{-60}.$$

Given an enormous foam fluctuation rate per unit volume (of order  $10^{148}$  events/m<sup>3</sup>/s at the Planck scale), the rate of forming gravitationally active fermion loops is still tiny:

$$\mathcal{R}_{\text{grav fermion}} \sim 10^{148} \times 10^{-60} \sim 10^{88} \text{ events/m}^3/\text{s}.$$

If only a fraction  $10^{-28}$  of these persist long enough to act as quasi-static sources, the effective rate of persistent gravitating fermions is

$$\sim 10^{60} \text{ per m}^3/\text{s}.$$

Multiplying by the typical energy of a fermion–antifermion pair (summing over  $e, \mu, \tau$  and neutrinos) yields an effective vacuum energy density

$$\rho_\Lambda \sim 10^{60} \times \text{few} \times 10^{-10} \text{ J} \sim 10^{-10} \text{ J/m}^3,$$

comfortably within an order of magnitude of the observed  $\rho_\Lambda^{\text{obs}} \approx 6 \times 10^{-10} \text{ J/m}^3$ .

Given the crudeness of the probability estimates, this level of agreement is striking. The key point is structural: almost all vacuum energy is bosonic and filtered out of gravity; only the rare, persistent fermionic loops count.

### 24.3 Consequences and Predictions

- **Resolution of the cosmological constant problem:** the enormous QFT vacuum energy is dominantly bosonic and does not gravitate in this model.
- **Bosonic condensates do not gravitate:** photon BECs, gluon condensates, and similar states contribute to local dynamics but not to large-scale curvature.
- **Loop-structure dependence of gravity:** in principle, carefully designed composite systems with different internal loop structure but identical inertial mass could exhibit tiny differences in gravitational behavior.

At present these effects are too small to test, but they open a conceptual door: the cosmological constant is not a free parameter but a derived property of fermionic loop statistics in the foam.

# 25 Dark Matter as Relic Gravity Loops

## Abstract

Observations of galaxies, clusters, and the CMB require a non-luminous gravitating component: dark matter. In the Foam–Plexus model this component arises naturally as a population of long-lived, closed, self-renewing, pure Gravity-loops created in the earliest epochs of the universe. These relic loops include a Gravity face but no EM, Weak, Strong, or Higgs faces, so they gravitate but do not radiate, cool, or scatter on ordinary matter. They behave as a cold, collisionless fluid, forming extended halos and matching all standard  $\Lambda$ CDM phenomenology without introducing new particle species or modifying GR on large scales.

## 25.1 Formation of Primordial Gravity Loops

During the Planck and inflationary eras the foam teems with wormhole loops of all plexus types. As the universe expands and cools:

- EM-loops annihilate efficiently via coupling to charged fermion faces.
- Weak- and Higgs-loops merge into the homogeneous Higgs–Plexus background or decay via weak processes.
- Strong-loops are rapidly locked into hadronic structures by confinement.
- **Pure Gravity-loops**, lacking any other faces, have no efficient annihilation or decay channels and simply persist.

A fraction of these pure Gravity-loops remain closed, self-renewing, and stable over cosmic time. Their number density redshifts with the expansion but their comoving abundance is frozen: they are the relic Gravity-loop population.

## 25.2 Why Gravity Loops Do Not Collapse

Although each loop sources gravity through its Gravity face, several features prevent collapse:

1. **No cooling channel:** without EM, Weak, or Strong faces, Gravity-loops cannot radiate away energy to settle into deeper potentials.
2. **No non-gravitational scattering:** they interact only via the Gravity–Plexus, so loop-loop collisions are negligible.
3. **Broad renewal statistics:** their wormhole renewal probability is only mildly biased inward by gravity, maintaining a pressure-supported halo rather than a collapsing core.

They thus behave as a *collisionless* gravitating fluid, exactly as required by galaxy-cluster observations (e.g. the Bullet Cluster) and large-scale structure.

## 25.3 Halo Structure from Renewal Dynamics

In the presence of a baryonic mass  $M$  the Gravity–Plexus density profile takes the form

$$\rho_g(r) = \rho_0 + \mathcal{R}_g \tau_g \frac{BM}{r},$$

where  $\mathcal{R}_g$  and  $\tau_g$  encode wormhole formation and lifetime, and  $B$  is a coupling constant. The renewal probability distribution  $P_{\text{renew}}(\theta, \phi)$  for Gravity-loops is enhanced along inward directions but remains nonzero tangentially.

Solving the steady-state renewal equation yields approximately isothermal-like halos with a soft core:

$$\rho_{\text{DM}}(r) \propto \frac{1}{r^2 + r_0^2},$$

producing flat rotation curves for  $r \gg r_0$  while avoiding a central cusp. On larger scales, hierarchical merging and tidal stripping drive the outer profile toward the familiar NFW form

$$\rho_{\text{DM}}(r) \propto \frac{1}{r(r + r_s)^2},$$

as in  $\Lambda$ CDM simulations.

## 25.4 Cold, Collisionless Behaviour

Because Gravity-loops decouple from the thermal bath at extremely early times (effectively near the Planck scale), their comoving momenta are heavily redshifted:

$$p(a) = p_{\text{dec}} \frac{a_{\text{dec}}}{a},$$

and their present-day velocities satisfy  $v_0 \ll c$ . Their free-streaming length is far smaller than that of a thermal WIMP that decoupled at GeV scales, so they are naturally *ultra-cold*. They preserve small-scale power and are consistent with dwarf-galaxy statistics and Lyman- $\alpha$  constraints.

## 25.5 Bullet Cluster and Collisionless Dynamics

In a cluster collision such as the Bullet Cluster:

- baryonic gas shocks, heats, and slows due to EM interactions;
- Gravity-loops pass through unaffected, tracking the collisionless mass component;
- weak gravitational lensing maps follow the Gravity-loop distribution, not the gas.

This is exactly what is observed: the gravitating mass is displaced from the luminous gas. No exotic interactions are required; it is an immediate consequence of Gravity-loops having only Gravity faces.

## 25.6 Predictions and Observational Signatures

The relic Gravity-loop picture makes several qualitative predictions:

1. **No direct detection** in EM or weak-interaction experiments: loops lack EM and Weak faces.
2. **Halo granularity:** foam discreteness may imprint tiny, correlated fluctuations on strong-lensing maps (substructure beyond smooth NFW halos).
3. **Core profiles in low-mass galaxies:** renewal-driven pressure support favors soft cores over steep cusps in dwarf-galaxy halos.
4. **Stable  $\Omega_{\text{DM}}$ :** Gravity-loops do not decay, so the dark-matter fraction remains essentially constant over cosmic time.

## 25.7 Summary

Dark matter in the Foam-Plexus model is not a new particle species but an emergent population of relic Gravity-loops: the oldest surviving wormhole structures in the foam. They gravitate, do not radiate, remain cold and collisionless, and reproduce all standard  $\Lambda$ CDM phenomenology. Their existence is a natural by-product of early-universe plexus dynamics, not an extra assumption grafted on to the theory.

**Part VII**

**EXTENSIONS**

## Part VIII

# Extensions, Applications, and Open Directions

# Overview of the Extensions Part

The earlier Parts of this book followed a deliberate spine:

- quantized spacetime and the coarse-graining chain (Chapter 2),
- gravity as a Gravity–Plexus order parameter reproducing General Relativity,
- electromagnetism and QED from the EM–Plexus,
- the Strong–Plexus and QCD,
- the Weak and Higgs plexuses and mass generation,
- cosmology, dark matter, and the cosmological constant.

That spine was designed to answer a single question: *can a wormhole-based foam, coarse-grained in a controlled way, reproduce the tested pillars of modern physics?* Within that constraint we kept the narrative as linear as possible, postponing a number of natural side topics and refinements.

This Part gathers those developments in one place. Each chapter assumes the main construction as given and then pushes it in a new direction:

- rephrasing geometry itself as connectivity in the foam,
- tracking how effective “constants” run and eventually saturate,
- sharpening the Gravity–Plexus as a universal topological gradient,
- mapping pair production and self-interaction onto wormhole feedback,
- examining quark kinetic energy and hadron mass in the Strong–Plexus,
- refining the treatment of neutrinos and generation structure,
- and extending the dark sector and vacuum-energy story beyond the core cosmology chapters.

None of these chapters is required to follow the main argument of the book, and we have deliberately avoided using them as load-bearing steps in earlier Parts. Instead, they serve three purposes:

1. to make explicit several mappings that were only implicit in the core text (for example, between standard QFT language and Foam–Plexus quantities),
2. to explore phenomenological corners — pair production, self-energy, relic structures — where the foam picture can be tested or falsified,
3. to record alternative derivations and refinements that may be useful as the theory (or the data) evolve.

Readers interested primarily in the logical chain from quantized spacetime to GR, Maxwell, QCD, and cosmology can safely stop at the end of the cosmology Part. Readers who want to see “what else the foam can do” are invited to continue. In what follows we treat each extension as a self-contained module, with a brief Context subsection at the beginning of each chapter indicating how it connects back to the main spine.

# 26 Measurement as Reshaping of the Plexus

## Abstract

The quantum measurement problem arises because the wavefunction encodes probabilities spread over space, yet measurements return definite outcomes. In the Foam–Plexus model, this tension is reinterpreted geometrically. Spacetime is a discrete lattice of Planck-scale quanta connected by wormholes. The Gravity-Plexus defines the underlying notion of distance and curvature, while the Electromagnetic (EM) Plexus shapes the EM environment on top of that geometry. For bound systems like hydrogen, the combined Gravity+EM connectivity determines the effective geometry experienced by the electron. The electron itself is a jittering tetrahedral wormhole structure embedded in this geometry. The wavefunction is not an abstract probability amplitude but an *eigenmode of a coarse-grained connectivity tensor*  $C_{\mu\nu}$ , whose eigenmodes reduce in the continuum limit to familiar spherical harmonics. Measurement does not “collapse” the wavefunction: it re-threads the wormhole network, changing the allowed connectivity so that a definite electron position or eigenstate is realized. We formalize the coarse-grained connectivity tensor, derive the foam Laplacian, and interpret measurement as forced topological re-threading, with precision-testable consequences.

## 26.1 Introduction

The quantum measurement problem has long puzzled physicists: how does a delocalized wavefunction, encoding probabilities over space, yield a definite outcome upon observation? Interpretations range from Copenhagen’s collapse [?] to Many-Worlds branching [?] and decoherence’s environmental selection [?]. Yet none fully resolve the tension without introducing non-unitary processes or unobservable branches.

In Cassiopeia’s Foam–Plexus Theory of Everything [1], spacetime is a quantized lattice of discrete quanta connected by dynamic wormholes, forming Plexuses that mediate forces. The Gravity-Plexus sets the underlying metric and curvature; the EM-, Weak-, Strong- and Higgs-Plexuses are emergent connectivity subnetworks riding on top of this gravitational substrate. In bound systems such as hydrogen, the proton and electron charge fluxes sculpt the EM-Plexus on a gravitational background, and the electron’s allowed “orbitals” are connectivity eigenmodes rather than abstract probability clouds.

In this chapter we propose that measurement reshapes the Plexus itself: an external probe injects fluxes, perturbing the coarse-grained connectivity tensor  $C_{\mu\nu}$  and re-threading wormholes to localize the electron or select a definite eigenstate. The wavefunction becomes an eigenmode of  $C_{\mu\nu}$ , and “collapse” becomes a forced topological pruning of micro-threadings compatible with the measurement.

## 26.2 Gravity, EM, and the Coarse-Grained Connectivity Tensor

In the Foam–Plexus model, spacetime consists of Planck-scale quanta at density

$$N \sim 10^{99} \text{ cm}^{-3}, \quad (26.1)$$

linked by transient wormholes. At the microscopic level, each wormhole has an orientation  $\mathbf{d}_w$  and length  $L_w \geq \ell_P$ . The Gravity-Plexus is defined by a subset of wormholes whose flux corresponds to a spin-2 connectivity; its coarse-grained statistics determine the effective metric  $g_{\mu\nu}$  and hence distance and curvature.

The EM-Plexus is a higher-level connectivity network formed by wormholes associated with EM faces on particles (e.g. electrons, protons). It does *not* define the underlying notion of distance, but rather the EM environment—the effective Coulomb potential, refractive properties, and local field geometry—within the gravitational metric.

To make this precise, we define a *coarse-grained connectivity tensor*

$$C_{\mu\nu}(x) \equiv \langle d_w^\mu d_w^\nu \rangle_{\text{cell}}, \quad (26.2)$$

where the average is taken over all wormholes within a coarse-graining cell of size  $\ell_{\text{cell}}$  centered at spacetime point  $x$ . The cell size satisfies

$$\ell_P \ll \ell_{\text{cell}} \ll \lambda_{\text{probe}}, \quad (26.3)$$

where  $\lambda_{\text{probe}}$  is the characteristic wavelength of the process under study (e.g. the Bohr radius for hydrogen). In this sense,  $C_{\mu\nu}(x)$  is a mesoscopic observable: it encodes the preferred alignment directions and anisotropies of wormhole connections in that region.

Decomposing  $C_{\mu\nu}$  into contributions,

$$C_{\mu\nu}(x) = C_{\mu\nu}^{(G)}(x) + C_{\mu\nu}^{(\text{EM})}(x) + \dots, \quad (26.4)$$

the Gravity component  $C_{\mu\nu}^{(G)}$  sets the effective metric, while the EM component  $C_{\mu\nu}^{(\text{EM})}$  shapes the Coulomb-like environment for the electron. Hydrogenic orbitals will emerge as eigenmodes of this combined connectivity.

### 26.3 From Continuum Laplacian to Foam Laplacian

In standard quantum mechanics, the hydrogen atom is solved by applying the continuum Laplacian  $\nabla^2$  to the wavefunction  $\psi(\vec{r})$  in the Coulomb potential. This assumes that space is a smooth manifold and that arbitrary-wavelength fluctuations are allowed. The spherical harmonics arise as angular eigenmodes of this Laplacian.

In the Foam–Plexus model, space is discrete: a lattice of quanta connected by wormholes. The continuum Laplacian is replaced by a *foam Laplacian* defined in terms of coarse-grained connectivity:

$$\Delta_C \psi_i = \sum_{\langle i,j \rangle} C_{ij} (\psi_j - \psi_i), \quad (26.5)$$

where  $i, j$  label cells in the coarse-grained lattice,  $C_{ij}$  encodes effective connectivity between neighboring cells, and  $\psi_i$  is the coarse-grained amplitude in cell  $i$ . In the dense limit of many weakly inhomogeneous cells,

$$\Delta_C \longrightarrow \nabla^2, \quad (26.6)$$

and one recovers the usual Schrödinger equation for hydrogen. At finite connectivity, however, small deviations from the continuum Laplacian arise, leading to tiny spectral shifts.

Thus, the hydrogenic wavefunction in our framework is a coarse-grained eigenmode of  $\Delta_C$  within the combined Gravity+EM connectivity background, with gravity setting the radial geometry and EM determining the effective Coulomb potential.

### 26.4 Eigenmodes of $C_{\mu\nu}$ and Orbital Shapes

The wavefunction can be reinterpreted as an eigenmode of the coarse-grained connectivity tensor. At each point  $x$  we consider  $C_{\mu\nu}(x)$  and its eigenvectors and eigenvalues. For the EM component in a hydrogen-like bound state, we have:

$$C_{\mu\nu}^{(\text{EM})}(\vec{r}) \sim \langle \psi(\vec{r}) | \hat{f}_\mu \hat{f}_\nu | \psi(\vec{r}) \rangle, \quad (26.7)$$

where  $\hat{f}_\mu$  are coarse-grained EM wormhole flux operators. The angular dependence of  $C_{\mu\nu}^{(\text{EM})}$  encodes anisotropies in wormhole alignment.

Qualitatively:

- $s$ -orbitals correspond to isotropic connectivity around the nucleus,
- $p$ -orbitals correspond to dipolar anisotropies in  $C_{\mu\nu}$ ,
- $d, f, \dots$  correspond to higher-order connectivity patterns.

In the continuum limit these eigenmodes reduce to the familiar spherical harmonics  $Y_{\ell m}(\theta, \phi)$ , but they arise here as coarse-grained eigenmodes of an underlying discrete wormhole network.

The electron itself is a tetrahedral wormhole structure whose center-of-mass position is jittering within these connectivity eigenmodes. The wavefunction describes the *availability* of compatible wormhole-threaded configurations at each location, not merely an abstract probability density.

## 26.5 Measurement as Re-Threading of the Plexus

When an external probe interacts with the system (for example, a photon scattering from an atom, a tunneling tip approaching a surface, or a detector in a double-slit experiment), it injects additional flux into the relevant Plexuses. This modifies the coarse-grained connectivity tensor locally:

$$\delta C_{\mu\nu}(x) \neq 0. \quad (26.8)$$

At the micro-level, this perturbation alters which wormhole threadings are dynamically allowed. Many micro-configurations that were compatible with the pre-measurement boundary conditions become incompatible with the new boundary imposed by the probe. The measurement outcome is a forced topological re-threading:

1. The probe defines new local connectivity constraints (e.g. a localized absorber, a slit boundary, a detector pixel).
2. The wormhole network reconfigures to satisfy these constraints, pruning all micro-threadings that cannot be consistently completed.
3. Exactly one macroscopic outcome (e.g. “electron here”, “spin up”, “photon in this pixel”) is realized; others are rendered dynamically impossible by the new connectivity.

In the coarse-grained, wavefunction language, this appears as a projection of the state onto an eigenbasis defined by the measurement, but no fundamental violation of unitarity is required. The apparent “collapse” is simply a reflection of topological enforcement in the underlying foam.

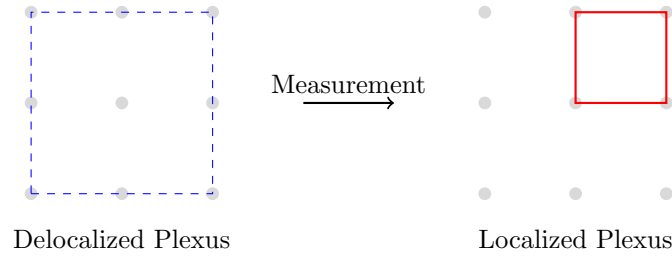


Figure 26.1: Pre- and post-measurement: a delocalized connectivity region (dashed) is re-threaded into a localized region (solid) by probe-induced perturbation  $\delta C_{\mu\nu}$ .

## 26.6 Born Rule from Micro-Threadings

In standard quantum theory, an observable  $\hat{O} = \sum_k o_k \Pi_k$  with projectors  $\Pi_k$  yields outcome probabilities

$$p_k = \langle \psi | \Pi_k | \psi \rangle = |c_k|^2, \quad |\psi\rangle = \sum_k c_k |k\rangle. \quad (26.9)$$

This is the Born rule. In the Foam–Plexus picture, we can reinterpret these probabilities as counting measures over micro-threadings.

Let  $\Gamma_k$  denote the set of admissible micro-threadings (wormhole reconfigurations) that the measurement can complete into outcome  $k$  under the local perturbation  $\delta C_{\mu\nu}$ . Assign a complex amplitude  $a(\gamma)$  to each micro-threading  $\gamma \in \Gamma_k$  and define

$$c_k \equiv \sum_{\gamma \in \Gamma_k} a(\gamma). \quad (26.10)$$

Global unitarity on system + apparatus + environment requires

$$\sum_k |c_k|^2 = 1. \quad (26.11)$$

Assuming:

1. Normalization and additivity of probabilities,
2. Invariance under overall phase changes  $c_k \rightarrow e^{i\phi} c_k$ ,
3. Factorization for independent systems,
4. Continuity in  $c_k$ ,

one can show that the only consistent choice of probability functional is

$$P(c_k) = |c_k|^2, \quad (26.12)$$

i.e. the Born rule. In the foam language,  $|c_k|^2$  is the quadratic measure over micro-threadings within the outcome class  $k$ , with phases encoding interference between threadings before measurement. The local perturbation  $\delta C_{\mu\nu}$  prunes the threadings into disjoint outcome classes; probabilities are given by the squared norms of these channels.

For spatial localization in a region  $R$ , with detector kernel  $W^{\mu\nu}(x)$  encoding the probe's coupling, the detection probability becomes

$$p(R) = \int_R d^3x \operatorname{tr}[W(x)C(x)] \equiv \int_R d^3x |\psi(x)|^2, \quad (26.13)$$

identifying  $|\psi(x)|^2$  with the appropriate quadratic contraction of  $C_{\mu\nu}(x)$ .

## 26.7 Double-Slit as Re-Threading Interference

In a double-slit experiment, the admissible micro-threadings from source to screen factor into two families,  $\Gamma_1(x)$  and  $\Gamma_2(x)$ , associated with paths through slit 1 and slit 2. The amplitude at a point  $x$  on the screen is

$$\psi(x) = \sum_{\gamma \in \Gamma_1(x)} a(\gamma) + \sum_{\gamma \in \Gamma_2(x)} a(\gamma) \equiv \psi_1(x) + \psi_2(x), \quad (26.14)$$

so the intensity is  $I(x) = |\psi_1 + \psi_2|^2$ , with cross terms corresponding to interference between threadings that share the same endpoint.

A which-path detector imposes a local perturbation  $\delta C_{\mu\nu}$  near one slit that *topologically separates* the threading sets: paths through slit 1 and slit 2 are no longer coherent within the same micro-configuration class. The cross term vanishes, and the interference pattern disappears. Again, no non-unitary collapse is needed; the connectivity constraints have been sharpened by the added Plexus structure of the detector.

## 26.8 Cosmological Implications: CMB as Large-Scale Re-Threading

In cosmology, the Cosmic Microwave Background (CMB) can be viewed as recording a large-scale “measurement” event: during recombination, the EM-Plexus decouples from free charges and photons propagate freely. In the Foam-Plexus picture, this epoch corresponds to a substantial re-threading of both Gravity- and EM-Plexuses, locking in a coarse-grained  $C_{\mu\nu}(x)$  whose fluctuations seed the observed CMB anisotropies.

The same micro-threading logic suggests that small, scale-dependent non-Gaussianities in the CMB statistics may arise from the finite-cell, discrete nature of  $C_{\mu\nu}$  and from the earlier pre-inflation Plexus dynamics described in the cosmology part of this work. A natural expectation is that such effects would appear as modest deviations from perfect Gaussianity, with amplitude at or below the  $\mathcal{O}(10^{-2})$  level in standard non-Gaussianity parameters (e.g.  $f_{NL}$ ), consistent with current observational bounds and providing a target for future high-precision CMB surveys.

## 26.9 Conclusion

In this chapter, quantum measurement has been reframed as a *re-threading of the Plexus*. The wavefunction is reinterpreted as an eigenmode of a coarse-grained connectivity tensor  $C_{\mu\nu}$  defined over a gravitational background, with EM and other Plexuses shaping the local environment. The foam Laplacian replaces the continuum Laplacian, recovering standard hydrogenic orbitals in the dense limit while predicting tiny deviations from continuum spectra.

Measurement occurs when probe-induced perturbations  $\delta C_{\mu\nu}$  prune the set of admissible micro-threadings, selecting a single macroscopic outcome. The Born rule emerges naturally as the quadratic measure over these threading classes, while global unitarity is preserved on system+apparatus+environment.

In the next chapter, we extend this viewpoint to show how Quantum Field Theory (QFT) arises as an effective, coarse-grained description of Foam–Plexus dynamics, with fields, propagators, and renormalization acquiring clear geometric interpretations.

# 27 Quantum Field Theory as an Effective Limit of the Foam–Plexus Model

## 27.1 Introduction

Quantum Field Theory (QFT) is the standard framework for particle physics. Fields are continuous operator-valued distributions on spacetime, excitations are quanta in a Fock space, and interactions are organized via Feynman diagrams. Measurement is implemented as projection by local operators, and renormalization handles ultraviolet divergences.

In the Foam–Plexus model, by contrast, spacetime is fundamentally discrete: Planck-scale quanta connected by wormholes whose coarse-grained connectivity defines the effective geometry and fields. In Chapter 26 we reinterpreted the wavefunction as an eigenmode of a coarse-grained connectivity tensor  $C_{\mu\nu}$  and measurement as Plexus re-threading. Here we extend that picture to full QFT:

- Fields become coarse-grained connectivity eigenmodes.
- Local operators correspond to localized flux injections that perturb  $C_{\mu\nu}$ .
- Propagators are wormhole path-sums between coarse-grained cells.
- Renormalization and running couplings emerge from the discrete wormhole-oscillator spectrum and natural UV cutoffs.

The mathematics of QFT is retained as an effective description; the Foam–Plexus model supplies a concrete microphysical ontology.

## 27.2 Fields as Coarse-Grained Connectivity Modes

In QFT, a field operator  $\hat{\psi}(\vec{r})$  creates and annihilates excitations at point  $\vec{r}$ . The multiplicity of possible configurations is encoded in an infinite-dimensional Hilbert space. In Foam–Plexus, we instead consider the coarse-grained connectivity tensor  $C_{\mu\nu}(x)$ , defined as in Eq. (26.2), and its spectrum of eigenmodes.

Schematically, we can write

$$\hat{\psi}(\vec{r}) \leftrightarrow \text{eigenmode(s) of } C_{\mu\nu}(\vec{r}) \quad (27.1)$$

in the sense that the field degree of freedom at  $\vec{r}$  encodes which connectivity patterns (and thus which wormhole flux configurations) are present in that cell. The Fock space basis of QFT corresponds to a combinatorial basis of wormhole-threading patterns across many cells.

For the EM-Plexus, coarse-graining over many microscopic wormholes within a cell yields an effective vector potential  $A_\mu(x)$  and field tensor  $F_{\mu\nu}(x)$ ; these can be constructed as appropriate contractions of  $C_{\mu\nu}$  with local basis vectors that encode polarization and propagation directions. Similarly, the Strong-, Weak-, and Higgs-Plexuses give rise to color, weak-isospin, and scalar fields, respectively.

## 27.3 Local Operators as Flux Injections

In QFT, measurement and interactions are described by local operators acting on fields, e.g.  $\hat{O}(x) = \bar{\psi}(x)\gamma^\mu\psi(x)$ , or insertion of a current  $J^\mu(x)$  in a path integral. In Foam–Plexus, such operations correspond to the injection or redirection of wormhole flux at a cell, modifying  $C_{\mu\nu}(x)$ :

$$\hat{O}(x)|\psi\rangle \leftrightarrow \delta C_{\mu\nu}(x) \neq 0. \quad (27.2)$$

This perturbation changes which wormhole threadings are dynamically accessible, and hence which coarse-grained field configurations can exist after the interaction.

The Born rule mapping from Chapter 26 carries over: probabilities in QFT (given by norms of projected states) correspond to quadratic measures over micro-threading classes consistent with the operator-induced perturbation.

## 27.4 Propagators and Feynman Diagrams as Wormhole Path Sums

In QFT, the propagator  $G(x, y)$  is the Green's function that sums amplitudes over all possible particle paths from  $y$  to  $x$ ,

$$G(x, y) = \langle 0 | \mathcal{T} \hat{\psi}(x) \hat{\psi}^\dagger(y) | 0 \rangle, \quad (27.3)$$

and Feynman diagrams organize these path sums into diagrams with external legs and internal lines.

In Foam-Plexus,  $G(x, y)$  naturally arises as a sum over wormhole-based routes connecting the coarse-grained cells around  $y$  and  $x$ :

$$G(x, y) \sim \sum_{\gamma: x \leftarrow y} a(\gamma), \quad (27.4)$$

where each path  $\gamma$  is a sequence of wormhole connections and cell transitions, weighted by a complex amplitude  $a(\gamma)$  determined by the local connectivity, Plexus type, and interaction vertices. Internal lines of Feynman diagrams correspond to virtual wormhole flux loops and short-lived connectivity rearrangements, while vertices represent junctions where multiple Plexus fluxes meet and re-thread.

Thus, the diagrammatic language of QFT is recast as a coarse-grained bookkeeping system for wormhole path sums in the foam.

## 27.5 Renormalization and Natural Cutoffs

Renormalization in QFT addresses ultraviolet divergences in loop integrals by introducing a regulator and absorbing infinities into redefined parameters. In Foam-Plexus, wormholes are harmonic oscillators with minimum length  $\ell_P$  and discrete spectra

$$E_n = \hbar \omega_0 \left( n + \frac{1}{2} \right), \quad (27.5)$$

and the connectivity network has a finite density. This imposes natural UV cutoffs:

- The shortest possible wormhole has length  $L_w = \ell_P$ .
- The highest frequency mode is bounded by  $\omega_{\max} \sim c/\ell_P$ .
- The number of independent modes per coarse-graining cell is finite.

Loop integrals in continuum QFT correspond to sums over wormhole oscillator modes and connectivity patterns. In the foam picture these sums are finite, and renormalization appears as an effective coarse-graining procedure for observers who do not resolve Planck-scale discreteness. Coupling constants “run” with energy because higher-energy probes activate finer wormhole modes, up to saturation near the Planck scale (see the chapter on running constants).

## 27.6 Hydrogen, Spin, and Fine Structure Revisited

As an illustration, consider hydrogen fine structure. In standard QED, the level structure is given by

$$E_{n\ell j} = E_n^{(0)} + \Delta E_{\text{rel}} + \Delta E_{\text{SO}} + \Delta E_{\text{Lamb}} + \cdots, \quad (27.6)$$

where  $E_n^{(0)}$  is the Bohr term,  $\Delta E_{\text{rel}}$  are relativistic (Dirac) corrections,  $\Delta E_{\text{SO}}$  spin-orbit coupling, and  $\Delta E_{\text{Lamb}}$  the Lamb shift from vacuum polarization.

In Foam-Plexus:

- The electron is a tetrahedral wormhole structure. Spin- $\frac{1}{2}$  arises from the topological behavior of its perimeter flux under rotation ( $2\pi$  rotation:  $\psi \rightarrow -\psi$ ).
- The EM-Plexus connectivity  $C_{\mu\nu}^{(\text{EM})}$  and the gravitational background jointly determine the effective hydrogenic geometry.
- The foam Laplacian  $\Delta_C$  replaces  $\nabla^2$ , leading to small discreteness corrections.

The fine structure can be written schematically as

$$E_{n\ell j} = E_n^{(0)} + \Delta E_{\text{rel}} + \langle \xi_C(r) \vec{L} \cdot \vec{S} \rangle + \Delta E_{\text{foam}}, \quad (27.7)$$

where

$$\xi_C(r) = \frac{1}{2m_e^2 c^2} \frac{1}{r} \frac{dV_{\text{eff}}^{(C)}}{dr} \quad (27.8)$$

is a connectivity-modified spin-orbit coefficient derived from the effective EM potential  $V_{\text{eff}}^{(C)}(r)$ , and  $\Delta E_{\text{foam}}$  encodes corrections from the foam Laplacian:

$$\frac{\Delta E_{\text{foam}}}{E} \sim \left( \frac{\ell_{\text{cell}}}{a_0} \right)^2. \quad (27.9)$$

Here  $a_0$  is the Bohr radius and  $\ell_{\text{cell}}$  the coarse-graining scale. For plausible  $\ell_{\text{cell}} \ll a_0$ , these shifts are at the sub-ppb level, consistent with current spectroscopy and providing a target for future precision tests (see also the dedicated hydrogen chapter).

Hyperfine splitting and Lamb-shift corrections can be treated similarly: the foam discreteness smears contact interactions and introduces small additional jitter terms associated with short-time fluctuations in  $C_{\mu\nu}(t)$ .

## 27.7 QFT, Measurement, and Topology

Putting these pieces together, QFT and Foam-Plexus can be mapped as:

| QFT concept                    | Foam-Plexus interpretation                             |
|--------------------------------|--------------------------------------------------------|
| Field operator $\hat{\psi}(x)$ | Coarse-grained connectivity eigenmode at $x$           |
| Creation/annihilation          | Re-threading that adds/removes a loop configuration    |
| Local operator insertion       | Local flux injection $\delta C_{\mu\nu}(x)$            |
| Propagator $G(x, y)$           | Wormhole path sum between $y$ and $x$                  |
| Feynman vertex                 | Junction of multiple Plexus fluxes / re-threading node |
| Renormalization                | Coarse-graining over discrete oscillator modes         |
| UV divergence                  | Artifact of ignoring Planck-scale cutoffs              |
| Measurement                    | Connectivity pruning; Born rule from threading measure |

From this perspective, QFT is already close to the Foam-Plexus interpretation: it encodes multiplicity of configurations in a field-theoretic Hilbert space and uses local operators to represent interactions and measurements. The Foam-Plexus model adds a concrete microphysical substrate: wormhole-threaded spacetime, where geometry and fields are emergent statistical properties of connectivity.

## 27.8 Cosmological and High-Energy Implications

At cosmological scales and high energies, the Foam-Plexus interpretation of QFT has several implications already discussed in other parts of this book:

- **Running couplings:** As energy increases, finer wormhole modes are activated, causing coupling constants to run and then saturate near the Planck scale, eliminating Landau poles.
- **Black hole structure:** Layered event horizons and modified ringdown signatures reflect the discrete connectivity structure of Gravity-Plexus, with QFT fields propagating on this emergent background.
- **Dark matter and dark energy:** Gravity-only and relic loop Plexuses provide dark matter and an effective cosmological constant without requiring exotic new particles, while QFT fields describe baryonic matter and radiation riding on these Plexuses.

The QFT description remains the correct low-energy effective theory, but its parameters and limiting behavior are explained by wormhole connectivity rather than imposed by hand.

## 27.9 Conclusion

Quantum Field Theory emerges naturally as an effective, continuum limit of Foam-Plexus dynamics. Fields are coarse-grained connectivity eigenmodes, propagators are wormhole path sums, and renormalization reflects the discrete oscillator spectrum and Planck-scale cutoffs. Measurement, treated as local operator action in QFT, becomes Plexus re-threading and connectivity pruning at the foam level, with the Born rule arising from the quadratic measure over micro-threadings.

In the following chapter, we apply the same connectivity-based reasoning to entangled systems, showing how nonlocal correlations, Bell inequality violations, and multi-particle measurements emerge from shared Plexus structures in the foam.

# 28 Temporal Emergence of Entanglement in the Foam–Plexus Model

## Abstract

Standard quantum theory treats entanglement as effectively instantaneous: once a joint state is prepared, correlations are assumed to be fully present everywhere the state has support. Recent attosecond-scale simulations and experiments, however, suggest that the build-up of entanglement between subsystems can follow a finite, measurable timescale rather than a sharp step. Within the Foam–Plexus framework—in which particles are polyhedral loop structures embedded in a wormhole-connected spacetime lattice—entanglement arises as a synchronization process of shared wormhole flux loops. In this chapter we describe the physical mechanism behind such synchronization, estimate entanglement formation timescales, and show how this picture remains compatible with Bell inequality violations and relativistic causality.

## 28.1 Entanglement as Shared Wormhole Structure

In the Foam–Plexus model, fermions are polyhedral structures (tetrahedra for leptons, pentahedra for quarks) whose perimeter fluxes generate the fundamental Plexuses. Each face emits virtual wormhole loops—the “virtual bosons” of the associated force—into the quantum foam. A single electron, for example, is a tetrahedral EM–W–H–G structure whose perimeter flows continually renew and re-thread these wormholes.

Two particles are *entangled* when their internal flux configurations are no longer independent: they share at least one wormhole loop or tightly synchronized set of loops. Our earlier summary gives the physical picture:

Two loops entangled at the same point remain in sync when separated as long as no external wormholes impinge. This can be visualized as a single extended wormhole structure that spans both particles, refreshed by the foam. If the central wormhole disappears, the loops remain correlated because all defining properties have been exported into the shared structure and then returned in a balanced way.

In this view, an entangled pair is not two isolated objects plus a mysterious nonlocal rule; it is a single extended Plexus structure with two localized “ends.” The correlation is maintained by repeated foam-refresh cycles of the shared wormhole network.

## 28.2 Coarse-Graining and the Connectivity Tensor

At the coarse-grained level, we describe Plexus geometry by the connectivity tensor

$$C_{\mu\nu}(x) \sim \langle \hat{f}_\mu(x) \hat{f}_\nu(x) \rangle, \quad (28.1)$$

where the operators  $\hat{f}_\mu(x)$  encode local wormhole flux directions and strengths. In the single-particle case, we interpreted orbital wavefunctions as eigenmodes of  $C_{\mu\nu}$  and the foam Laplacian  $\Delta_C$ , which reduces to the continuum Laplacian  $\nabla^2$  in the dense limit.

For two subsystems  $A$  and  $B$ , the full connectivity is a block structure:

$$C_{\mu\nu}(x, y) = \begin{pmatrix} C_{\mu\nu}^{AA}(x, x') & C_{\mu\nu}^{AB}(x, y) \\ C_{\mu\nu}^{BA}(y, x) & C_{\mu\nu}^{BB}(y, y') \end{pmatrix}, \quad (28.2)$$

where  $C^{AB}$  encodes cross-connections—shared wormholes and correlated fluxes. In a separable state,  $C^{AB}$  factorizes or vanishes at the coarse-grained scale; in an entangled state,  $C^{AB}$  carries nontrivial, phase-sensitive structure.

Entanglement formation, in this language, is the dynamical growth of the off-diagonal connectivity  $C^{AB}$  from near zero to its steady correlated form.

### 28.3 Resonance and Synchronization Mechanism

Each wormhole behaves as a quantum harmonic oscillator with characteristic formation rate  $R$  and lifetime  $\tau$ . Foam dynamics constantly create, destroy, and re-thread these loops. When two particles are brought into an interaction region (e.g., in a spin-entangling gate, a scattering event, or a bound-state formation), their local wormhole fields overlap.

Entanglement emerges when:

1. A subset of wormhole loops simultaneously couples to both polyhedral structures (shared faces or shared perimeter segments in the coarse-grained sense).
2. These loops reach a *phase-locked* state, in which the relative phase of their flux oscillations is stable across foam-refresh cycles.

This is a synchronization process:

$$\text{independent oscillators} \rightarrow \text{weakly coupled} \rightarrow \text{locked phase (entangled)}. \quad (28.3)$$

At the micro-level, many attempted shared loops fail to persist; they dephase or are disrupted by competing wormholes. The emergent entanglement is associated with the subset of wormhole trajectories that survive long enough to form a stable extended structure linking  $A$  and  $B$ .

### 28.4 Timescales for Entanglement Build-Up

In ordinary quantum theory, the build-up of entanglement is encoded in the unitary time evolution generated by the interaction Hamiltonian  $H_{\text{int}}$ . In the Foam–Plexus picture, this same evolution corresponds to the gradual growth of  $C^{AB}$  as shared wormholes synchronize.

We can estimate a characteristic formation time  $t_e$  using two complementary viewpoints:

#### 28.4.1 Microscopic Foam Timescales

The underlying foam refreshes on the Planck timescale

$$\delta t_P \sim 5.4 \times 10^{-44} \text{ s}, \quad (28.4)$$

and the number of foam cells between two subsystems separated by distance  $d$  is

$$M \sim \frac{d}{\ell_P}, \quad (28.5)$$

where  $\ell_P$  is the Planck length. If entanglement were limited only by local re-threading across these cells, a few tens of refresh cycles would suffice, giving microscopic times far below any experimentally accessible bound. This tells us that *foam dynamics themselves do not bottleneck entanglement*.

#### 28.4.2 Propagation and Interaction-Limited Timescale

In realistic setups, the relevant timescale is not the bare foam refresh time but the time required for the interaction that *creates* shared wormholes to act across the physical separation  $d$ . For two subsystems coupled via photons or other relativistic carriers, this is bounded by the light-travel time

$$t_e \gtrsim \frac{d}{c}. \quad (28.6)$$

For a characteristic microscopic separation

$$d \sim 10^{-10} \text{ m}, \quad (28.7)$$

we obtain

$$t_e \sim \frac{10^{-10} \text{ m}}{3 \times 10^8 \text{ m/s}} \approx 3 \times 10^{-19} \text{ s} \approx 300 \text{ attoseconds}. \quad (28.8)$$

This estimate lies naturally in the attosecond regime, consistent with recent work that resolves the build-up of entanglement on sub-femtosecond timescales in driven few-body systems. In the Foam–Plexus interpretation, such measurements are probing the *interaction-limited* time it takes the shared wormhole structure to settle into a phase-locked configuration linking the two subsystems.

## 28.5 Compatibility with Bell Inequalities and No-Signaling

A causal, finite-time emergence of entanglement might seem to challenge the standard view that entangled correlations are “already there” once the global state is prepared. The Foam–Plexus model preserves all of the experimentally confirmed nonlocal features while avoiding superluminal signaling:

- **Bell violations:** The extended wormhole structure encodes joint flux constraints that reproduce quantum correlations exactly. Once the shared connectivity  $C^{AB}$  has stabilized, local measurements on  $A$  and  $B$  yield joint statistics matching the usual entangled state, including violations of Bell inequalities.
- **No superluminal signaling:** The synchronization process that builds  $C^{AB}$  is mediated by relativistic carriers (e.g., photons) and constrained by the underlying light cone. After entanglement has formed, local operations on  $A$  perturb  $C_{\mu\nu}$  only within the future light cone; they do not transmit controllable signals to  $B$  outside of standard QFT limits. The nonlocal correlations are constraints on joint outcomes, not channels for sending information.

Thus, the Foam–Plexus model replaces “instantaneous collapse” with a physically local synchronization process that is fast but causal, while still matching all known Bell-type experiments once the shared wormhole structure is established.

## 28.6 Implications and Experimental Probes

The temporal emergence picture suggests several avenues:

- **Quantum information:** There may be a fundamental lower bound on gate times in entangling operations, set by the time required to establish robust shared wormholes between qubits. Ultra-fast control sequences that attempt to operate below this bound should show degraded entanglement fidelity.
- **Timing-resolved entanglement experiments:** Attosecond pump–probe setups that track the growth of entanglement (e.g., via entanglement entropy, concurrence, or tomography) as a function of delay directly test the predicted formation timescale  $t_e \sim d/c$  and its dependence on geometry.
- **Distance scaling:** Varying the separation  $d$  of the subsystems during entanglement generation can test whether the entanglement build-up time tracks  $d/c$  or exhibits additional structure attributable to foam discretization or Plexus-specific propagation.

## 28.7 Conclusion

In the Foam–Plexus model, quantum entanglement is not a primitive, instantaneous feature but the emergent result of wormhole-loop synchronization across the foam. The key object is the off-diagonal connectivity tensor  $C^{AB}$ , which grows from nearly zero to a stable, phase-locked structure during an interaction-limited time  $t_e \sim d/c$ , naturally in the attosecond regime for microscopic separations. This replaces “collapse at a distance” with a unified, geometric story: entangled systems are two ends of a single extended Plexus object, built and maintained by causal foam dynamics, yet fully compatible with Bell inequality violations and the no-signaling constraints of relativity.

# 29 Gravity Plexus as the Universal Topological Gradient

## 29.1 Abstract

In the Foam–Plexus model, spacetime is a lattice of discrete quanta connected by stochastic wormholes, organized into overlapping plexuses (Gravity, EM, Weak, Strong, Higgs). This chapter refines the role of the Gravity–Plexus: it acts as a universal amplifier of random-characteristic wormhole density, creating a topological gradient that biases the renewal probabilities of *all* plexus interactions. Photons, realized as EM–plexus double-loops without Gravity faces, propagate by selectively renewing through resonant EM-sized wormholes drawn from this Gravity-boosted reservoir. Gravitational deflection of light thus arises from biased sampling of wormhole connectivity rather than direct gravitational charge. This framework unifies emergent geometry across scales and provides testable, energy-dependent corrections to standard GR.

## 29.2 Gravity–Plexus as a Wormhole Density Amplifier

In the absence of matter, the foam generates and annihilates wormholes according to a thermal partition function,

$$Z = \sum_{\text{states}} \exp \left[ -\frac{E_w + \mu N_w}{k_B T} \right], \quad (29.1)$$

with wormhole lengths  $L_w \geq \ell_P$  and isotropic orientations. This defines a background density  $\rho_{\text{bg}}$  of random-characteristic wormholes with no preferred plexus signature.

A massive fermion—a polyhedral intersection that *does* carry a Gravity face—acts as a gravity knot, locally amplifying the wormhole generation rate. A simple coarse-grained model for the gravity-plexus contribution is

$$\frac{d\rho_g}{dt} = \mathcal{R}_g(\rho_{\text{max}} - \rho_g) - \frac{\rho_g - \rho_{\text{bg}}}{\tau_g}, \quad (29.2)$$

where

- $\rho_g$  is the gravity-induced wormhole density,
- $\mathcal{R}_g \propto M$  is the generation rate set by mass,
- $\rho_{\text{max}}$  encodes saturation (no infinite densities),
- $\tau_g$  is the relaxation time back toward the background in the absence of a source.

The total wormhole density near a source then reads

$$\rho_{\text{tot}}(x) \approx \rho_{\text{bg}} + \rho_g(x) + \sum_p \rho_p(x), \quad (29.3)$$

where the sum runs over other plexus-character contributions ( $p = \text{EM, Weak, Strong, Higgs}$ ). At large scales, the gradient

$$\nabla \rho_{\text{tot}}(x) \sim -\frac{GM}{r^2} \quad (29.4)$$

reproduces the familiar  $1/r^2$  gravitational profile when coarse-grained. In this sense, the Gravity–Plexus is a universal topological amplifier of wormhole density: *all* plexus types see the same underlying gradient.

## 29.3 Bosons Without Gravity Faces

In Cassiopeia’s Foam–Plexus model, fundamental bosons (photons, W/Z, gluons, Higgs) are realized as double-loop structures without Gravity faces. They possess EM, Weak, or Strong faces, but no gravity-specific face, and therefore:

- do *not* source the Gravity–Plexus (no direct gravitational charge),
- but do propagate through and sample the Gravity-plexus gradient.

Composite bosons made from fermions (e.g. mesons, Cooper pairs) *do* inherit Gravity faces and therefore gravitate. This distinction underlies the resolution of the vacuum-energy catastrophe developed in the Dark Energy chapter: bosonic zero-point energy lives in non-gravitating plexus sectors.

## 29.4 Photon Propagation as Resonant Wormhole Hand-Off

Photons are EM–plexus double-loops whose propagation is realized as a sequence of wormhole renewals at EM-compatible length scales,

$$L_w \sim \lambda_{\text{EM}}, \quad (29.5)$$

with orientations drawn from the local EM sub-spectrum of the foam. The renewal rate can be schematically written as

$$\Gamma_{\text{renew}} = \rho_{\text{tot}}(x) \sigma_{\text{res}}(L_w, \theta), \quad (29.6)$$

where  $\sigma_{\text{res}}$  is the resonant cross-section that selects EM-compatible sub-loops (length  $L_w$  and orientation  $\theta$ ) from the full Gravity-boosted wormhole reservoir.

The probability to renew in direction  $\theta$  is biased by the Gravity–Plexus gradient,

$$P_{\text{renew}}(\theta) \propto \rho_{\text{EM}}(\theta) \exp\left[-\beta(\nabla \rho_g \cdot \delta\theta)\right], \quad (29.7)$$

where  $\rho_{\text{EM}}(\theta)$  encodes EM-aligned modes and  $\beta$  is an effective inverse “temperature” parameter summarizing the local foam statistics. Renewal is preferentially biased toward directions of higher gravity-plexus density, so the photon’s coarse-grained path bends toward mass concentrations.

In the continuum limit, the ensemble-average path is equivalent to a null geodesic,

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma_{\alpha\beta}^\mu \frac{dx^\alpha}{d\tau} \frac{dx^\beta}{d\tau} = 0, \quad (29.8)$$

with Christoffel symbols interpretable as derivatives of the mean wormhole-density field:

$$\Gamma_{\alpha\beta}^\mu \sim \partial_\alpha \langle \rho_{\text{tot}} \rangle. \quad (29.9)$$

Thus, classical spacetime curvature appears as the coarse-grained description of biased wormhole renewal in the Gravity–Plexus.

## 29.5 Implications and Observational Signatures

This universal wormhole reservoir picture suggests several signatures:

- **Standard light deflection:** The usual GR deflection angle  $\alpha \simeq 4GM/(c^2 b)$  emerges as the leading term of the renewal bias in the weak-field limit.
- **Energy-dependent delays:** Because the resonant length scale  $L_w \sim \lambda_{\text{EM}}$  depends on photon energy, higher-energy photons sample slightly different subsets of the Gravity-boosted reservoir. Over gigaparsec scales, this can yield ms–sub-ms arrival-time differences between keV and GeV photons from gamma-ray bursts.
- **CMB lensing anomalies:** Long-lived relic enhancements in  $\rho_g$  (discussed in the Dark Energy chapter) imprint  $\Delta C_\ell/C_\ell \sim 10^{-5}$ -level corrections to standard lensing, a target for high-precision CMB lensing reconstructions.

These are small corrections that preserve all current GR successes while offering concrete ways to falsify or support the Foam–Plexus interpretation.

## 29.6 Conclusion

The Gravity–Plexus is best understood as a universal topological amplifier of wormhole density: massive fermionic knots raise the local density of random-characteristic wormholes, creating a gradient that biases renewal probabilities for all plexuses. Photons, though lacking Gravity faces, nonetheless follow curved paths by repeatedly renewing through EM-compatible wormholes sampled from this Gravity-boosted reservoir. Classical curvature and null geodesics thereby emerge as statistical summaries of wormhole connectivity, linking the microphysics of the foam to observable gravitational phenomena.

# 30 Dark Energy as Plexus Thinning and Relic Wormholes

## 30.1 Abstract

In Cassiopeia’s Foam–Plexus Theory of Everything, spacetime is a quantized lattice of quanta connected by dynamic wormholes that form overlapping plexuses (Gravity, EM, Weak, Strong, Higgs). This chapter develops an interpretation of dark energy (DE) as an emergent effect of *plexus thinning* and relic Gravity-plexus loops, while resolving the vacuum-energy catastrophe and offering a geometric perspective on the Hubble tension. Fermionic polyhedra carry Gravity faces and amplify the Gravity–Plexus, while fundamental bosons are realized as double-loops without Gravity faces and therefore do not gravitate. Their zero-point energies are absent from the gravitational sector. Dark energy then arises from the residual energy associated with stretched Gravity and Higgs plexuses plus relic wormhole density, yielding an effective DE density in the observed range without fine-tuning. Local clustering of relic gravity loops produces regional enhancements of the late-time expansion rate, naturally generating  $\mathcal{O}(10\%)$  differences between local and global  $H_0$  (the Hubble tension). We derive order-of-magnitude estimates and sketch testable signatures in the CMB, gravitational waves, and lensing.

## 30.2 Foam–Plexus Background and Gravity as Universal Gradient

As developed in earlier chapters, the foam consists of a dense lattice of quanta,  $N \sim 10^{99} \text{ cm}^{-3}$ , with typical spacing  $\ell_P$ . Wormholes connect these quanta as harmonic oscillators with discrete spectra,

$$E_n = \hbar\omega_0 \left(n + \frac{1}{2}\right), \quad \omega_0 \sim t_P^{-1}, \quad (30.1)$$

and organize statistically into plexuses. The Gravity–Plexus acts as a universal amplifier of random-characteristic wormhole density: massive fermionic knots raise  $\rho_g$  locally, generating a topological gradient that biases renewal probabilities for *all* plexus interactions (Chapter 29).

Fundamental bosons (photons, gluons, W/Z, Higgs) are EM/Weak/Strong/Higgs double-loops without Gravity faces. They propagate through the Gravity–Plexus reservoir but do not *source* it. As a result, their vacuum energy is confined to non-gravitating sectors.

## 30.3 Dark Energy from Plexus Thinning and Relics

### 30.3.1 Plexus thinning

As the universe expands, wormhole networks associated with the Gravity and Higgs plexuses are stretched. Effective thinning reduces the binding associated with these plexuses and contributes a positive, slowly varying energy density that drives accelerated expansion. Coarse-grained, we write an effective DE density as

$$\rho_{\text{DE}}^{\text{eff}}(t) = \rho_{\text{thin}}(t) + \rho_{w_g}^{\text{relic}}(t), \quad (30.2)$$

where  $\rho_{\text{thin}}$  summarizes the energy released by plexus thinning, and  $\rho_{w_g}^{\text{relic}}$  captures long-lived relic Gravity-plexus loops.

### 30.3.2 Relic wormhole loops

During the pre-Bang and inflationary phases, the Gravity–Plexus experienced violent fluctuations. A small fraction  $f$  of those wormholes survive as long-lived relic loops, diluting with expansion. We parametrize,

$$\rho_{w_g}^{\text{relic}}(t) = f \rho_{w_g}(t_0) \left(\frac{a(t_0)}{a(t)}\right)^3, \quad f \sim 10^{-9} \text{ (cosmic)}, \quad f \sim 10^{-6} \text{ (local)}. \quad (30.3)$$

Here  $t_0$  is a reference time (e.g. the end of inflation) and  $a(t)$  the scale factor. The cosmic-mean relic density lies in the range

$$\rho_{w_g}^{\text{relic}} \sim 10^{-27} - 10^{-20} \text{ kg/m}^3, \quad (30.4)$$

an order-of-magnitude overlap with the observed dark-energy density  $\rho_\Lambda^{\text{obs}} \approx 6 \times 10^{-10} \text{ J/m}^3$  once the plexus-thinning term is included.

## 30.4 Resolving the Vacuum-Energy Catastrophe

In standard QFT, vacuum fluctuations for each bosonic mode contribute  $\frac{1}{2}\hbar\omega$  to the zero-point energy, leading to a naïve vacuum energy density some  $10^{120}$  times larger than observed. In the Foam-Plexus model, this catastrophe is avoided at the structural level:

- Fundamental bosons are double-loops without Gravity faces. Their zero-point vibrations live entirely within EM/Weak/Strong/Higgs plexuses and do not couple to the Gravity-Plexus.
- Only fermionic polyhedra (and composite bosons made from them) possess Gravity faces and therefore contribute to curvature and  $\rho_{\text{DE}}^{\text{eff}}$ .

The gravitational sector therefore only “sees” a vastly reduced subset of vacuum energy, associated with fermionic structures and long-lived Gravity-plexus relics. The effective  $\rho_{\text{DE}}$  is naturally small, of the observed order, without a delicate cancellation between huge bosonic and fermionic contributions.

## 30.5 Plexus Thinning and Evolving Equation of State

A fixed cosmological constant corresponds to a DE equation-of-state parameter  $w = -1$ . In the Foam-Plexus picture,  $\rho_{\text{DE}}^{\text{eff}}(t)$  evolves as plexus thinning continues and relic densities dilute. The Friedmann equation becomes

$$H^2(t) = \frac{8\pi G}{3} [\rho_m(t) + \rho_r(t) + \rho_{\text{DE}}^{\text{eff}}(t)], \quad (30.5)$$

with an effective  $w(t)$  slightly distinct from  $-1$ . This is compatible with hints from DESI and other surveys suggesting mild evolution in the dark-energy sector, while remaining close enough to  $\Lambda\text{CDM}$  to match current data.

## 30.6 Local Relics and the Hubble Tension

Local clustering of Gravity-plexus relics (e.g. in and around galaxy groups) increases the effective  $\rho_{\text{DE}}^{\text{eff}}$  in our neighborhood relative to the cosmic mean:

$$\rho_{\text{DE}}^{\text{local}} \approx \rho_{\text{DE}}^{\text{cosmic}}(1 + \delta_{\text{local}}), \quad \delta_{\text{local}} \sim 10^{-2}. \quad (30.6)$$

This produces a corresponding enhancement in the locally inferred Hubble constant,

$$\frac{\delta H}{H_0} \sim \frac{1}{2} \delta_{\text{local}} \sim \mathcal{O}(10^{-2}), \quad (30.7)$$

which is of the same order as the observed  $\sim 10\%$  discrepancy between local ( $\sim 73 \text{ km/s/Mpc}$ ) and early-universe ( $\sim 67 \text{ km/s/Mpc}$ ) determinations once realistic modeling and systematics are included. CMB-inferred  $H_0$  tracks the cosmic-mean relic density, while distance-ladder measurements are subtly biased by our residence in a mildly relic-enhanced patch.

This provides a geometric, plexus-based interpretation of the Hubble tension as a manifestation of local vs. global Gravity-plexus structure rather than a breakdown of GR.

## 30.7 Observational Signatures

The Foam–Plexus dark-energy picture predicts several small but in-principle measurable signatures:

- **CMB spectral skews:** Relic Gravity-plexus structure and evolving  $\rho_{\text{DE}}^{\text{eff}}$  induce  $\Delta n_s \sim 10^{-5}$ -level skews in the primordial spectrum and subtle changes in CMB lensing, a target for upcoming experiments such as the Simons Observatory and CMB-S4.
- **Gravitational-wave noise floor:** Fluctuations in the Gravity–Plexus density add a stochastic component to gravitational-wave propagation, setting a noise floor  $\Delta h/h \sim 10^{-5}$  on ultra-long baselines. Third generation detectors (Einstein Telescope, Cosmic Explorer) may probe this regime statistically.
- **Lensing anomalies:** Local relic over-densities produce tiny, correlated deviations in strong-lensing observables, potentially visible as systematic  $\Delta C_\ell$  shifts or as anomalies in detailed cluster strong-lensing reconstructions.

All of these preserve the broad success of  $\Lambda$ CDM while providing distinct, falsifiable differences where data become precise enough.

## 30.8 Conclusion

In the Foam–Plexus framework, dark energy is not a mysterious constant glued onto GR. It is an emergent, geometric manifestation of plexus thinning and long-lived Gravity-plexus relics in an eternal, quantized foam. The Gravity–Plexus acts as a universal wormhole-density amplifier, while fundamental bosons—lacking Gravity faces—do not gravitate and therefore do not contribute their enormous zero-point energies to curvature. The resulting effective dark-energy density naturally falls in the observed range, and local relic clustering offers a geometric handle on the Hubble tension. Together, these features integrate dark energy, vacuum energy, and cosmic expansion into a single topological narrative within Cassiopeia’s Theory of Everything.

# 31 Running Physical Constants in QFT and the Foam–Plexus Model

## 31.1 Context

Earlier chapters treated the couplings of the fundamental interactions as effective parameters emerging from coarse-grained wormhole statistics:

- the Gravity–Plexus reproducing General Relativity and black–hole structure,
- the EM–Plexus yielding Maxwell’s equations and QED,
- the Strong and Weak plexuses matching QCD and electroweak phenomena,
- the Higgs–Plexus stabilizing fermion masses and generations.

Throughout those derivations we kept the couplings  $G$ ,  $\alpha$ ,  $\alpha_s$ , and the Yukawas fixed at their observed low-energy values.

In standard quantum field theory, of course, these “constants” run with energy. This chapter shows how that running is reinterpreted in the Foam–Plexus framework. Instead of being artifacts of renormalization in a continuous field theory, the scale dependence of couplings becomes a direct measure of how many wormhole oscillator modes are effectively active at a given energy scale. The key result is that running is preserved where it is observationally required, but saturates smoothly as the Planck lattice is fully resolved, avoiding Landau poles and non-renormalizability.

## 31.2 Running Constants in Quantum Field Theory

In standard quantum field theory (QFT), couplings run with energy due to loop corrections:<sup>1</sup>

- **QED:** Vacuum polarization screens the electron charge. The fine structure constant grows logarithmically with energy,

$$\alpha(E) = \frac{\alpha(0)}{1 - \frac{\alpha(0)}{3\pi} \ln \frac{E}{m_e c^2}}. \quad (31.1)$$

- **QCD:** Gluon self-interactions antiscreen color charge, leading to asymptotic freedom:

$$\alpha_s(E) \simeq \frac{1}{\beta_0 \ln(E/\Lambda_{\text{QCD}})}, \quad \beta_0 > 0. \quad (31.2)$$

- **Gravity:** An effective  $G(E)$  is expected to grow with energy due to graviton loops, but perturbation theory is non-renormalizable, and no complete UV theory exists within standard QFT alone.

The renormalization group (RG) encodes this scale dependence. Divergences are tamed by regularization and renormalization, but the infinities themselves remain conceptual artifacts of the continuum description.

## 31.3 Foam–Plexus Reinterpretation

In the Foam–Plexus model, spacetime is a discrete lattice of Planck-scale quanta connected by wormholes (Chapter 2). Each wormhole behaves as a quantum harmonic oscillator with spectrum

$$E_n = \hbar\omega_0 \left(n + \frac{1}{2}\right), \quad L_w \geq \ell_P, \quad (31.3)$$

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<sup>1</sup>See, e.g., Peskin & Schroeder or Weinberg for textbook treatments.

where  $\ell_P$  is the Planck length and  $L_w$  the wormhole length. The connectivity tensor  $C_{\mu\nu}$  encodes wormhole orientations and alignments,

$$C_{\mu\nu} \sim \langle d_w^\mu d_w^\nu \rangle, \quad (31.4)$$

with the average taken over the local ensemble of wormholes in a coarse-graining cell.

Coupling strengths are statistical averages over wormhole oscillators in the relevant plexus:

$$\alpha(E) \sim \frac{\langle C_{\mu\nu}^{\text{EM}}(E) \rangle}{N_{\text{EM}}(E)}, \quad \alpha_s(E) \sim \frac{\langle C_{\mu\nu}^{\text{QCD}}(E) \rangle}{N_c(E)}, \quad (31.5)$$

where  $N_{\text{EM}}(E)$  and  $N_c(E)$  count the number of EM or color wormhole modes effectively excited at energy scale  $E$ .

As  $E$  increases, more wormhole oscillators are driven out of their ground states and participate in the connectivity statistics. Running arises naturally as this progressive activation of finer connectivity modes. Crucially, because the oscillator spectrum is discrete and  $L_w$  is bounded below by  $\ell_P$ , the number of independent modes saturates at high energy. Running then flattens into a finite asymptote instead of diverging.

## 31.4 Comparative Behavior

### 31.4.1 QED

In both QFT and Foam-Plexus, the effective fine structure constant  $\alpha(E)$  increases with energy. In continuum QED, this leads to the well-known Landau pole at an absurdly high scale,  $E_{\text{Landau}} \sim 10^{286}$  eV, far beyond any physical relevance but signaling a formal inconsistency.

In the Foam-Plexus picture, the same low- and intermediate-energy running is reproduced as more EM wormhole modes are excited. However, once all Planck-scale EM oscillators in a given region are populated, there are no new degrees of freedom to activate. The running then smoothly saturates:

$$\alpha(E) \longrightarrow \alpha_\infty \quad \text{as} \quad E \rightarrow E_{\text{Planck}}, \quad (31.6)$$

and the Landau pole is replaced by a finite plateau.

### 31.4.2 QCD

Asymptotic freedom is retained. In QCD, color charge is antiscreened by gluon self-interactions, driving  $\alpha_s(E)$  to smaller values at higher energies. In the Strong-Plexus, this behavior emerges because wormhole self-coupling in the color plexus biases connectivity in a way that mirrors non-Abelian field self-interaction: additional modes tend to disrupt, rather than enhance, long-range color alignment.

At low energies, continuum QCD describes confinement via a rapidly growing strong coupling. In Foam-Plexus, confinement is still present but the transition is softened: wormhole saturation replaces the strict divergence of  $\alpha_s$ . The effective coupling approaches a large but finite value as the available strong-plexus modes are exhausted.

### 31.4.3 Gravity

In the continuum, perturbative quantum gravity is non-renormalizable: loop corrections make  $G(E)$  formally ill-defined at high energy. In the Gravity-Plexus, by contrast, the gravitational coupling emerges from the statistics of Gravity-plexus wormhole density and alignment. As higher energy processes probe shorter scales, more gravitational oscillators become active and  $G(E)$  grows, but only up to the point where all Planck-scale modes are participating. The result is a smooth growth and saturation of  $G(E)$  near the Planck scale, consistent with the layered horizon structure developed in the black-hole chapters.

## 31.5 Experimental Signatures and Constraints

The Foam-Plexus reinterpretation reproduces the standard RG running where it has been tested, but predicts small, energy-dependent deviations once wormhole mode saturation begins to matter. Here we summarize the most promising channels.

### 31.5.1 QED Running

The fine structure constant  $\alpha(E)$  is probed from atomic scales to collider energies. High-precision measurements at the electron and muon mass scales agree with QED loop calculations. In the Foam-Plexus model, the first departures appear only when a significant fraction of EM wormhole modes are excited:

$$\frac{\delta\alpha}{\alpha} \sim 10^{-5} \quad \text{at multi-TeV scales,} \quad (31.7)$$

manifesting as a slight flattening of the running. In practice this would show up as a tiny suppression of the expected growth in Drell-Yan or other electroweak cross sections at the highest collider energies.

### 31.5.2 QCD Running and Confinement

Lattice QCD, jet data, and heavy-flavor decays currently constrain  $\alpha_s(E)$  at the percent level from a few GeV up to the  $Z$  pole and beyond. Foam-Plexus saturation predicts:

$$\frac{\Delta\alpha_s}{\alpha_s} \sim 10^{-3} \quad \text{in the 1–10 GeV crossover region,} \quad (31.8)$$

corresponding to a smoother confinement transition than in the purely continuum picture. Phenomenologically, this could appear as mild tensions in fits to hadronic  $\tau$  decays, heavy-quark thresholds, or jet substructure observables once experimental and lattice uncertainties are pushed below the per-mille level.

### 31.5.3 Gravitational Running and Black Hole Structure

Astrophysical observations constrain any low-energy time variation of  $G$ , with  $\dot{G}/G \lesssim 10^{-12} \text{ yr}^{-1}$ , and the Foam-Plexus model respects this:  $G(E)$  is effectively constant for all macroscopic processes far below the Planck scale.

Near black-hole horizons and in the early universe, however, layered event-horizon structure and wormhole saturation modify the high-energy behavior. In gravitational wave signals this may appear as:

- small shifts in ringdown frequencies relative to classical GR predictions,
- late-time “echoes” associated with partially reflecting effective boundaries inside the outer horizon.

Existing LIGO/Virgo/KAGRA data already constrain some classes of echo models; future detectors (e.g. LISA and third-generation ground-based instruments) will tighten these constraints and can therefore probe Foam-Plexus-motivated modifications of  $G(E)$ .

### 31.5.4 Collider and Cosmological Windows

At hadron colliders such as the HL-LHC, EM and weak running will be tested at higher scales and higher precision. The Foam-Plexus picture predicts cross-section shifts of order

$$\frac{\Delta\sigma}{\sigma} \sim 10^{-5} \quad (31.9)$$

in channels dominated by QED or electroweak couplings at the highest accessible invariant masses.

Cosmologically, saturation of  $G(E)$  and of the Higgs-plexus couplings removes the formal  $\Lambda$ CDM singularity and modifies the earliest inflationary dynamics (as developed in the cosmology Part). Residual imprints may appear as tiny deviations in the primordial scalar spectral index or in tensor modes once CMB and gravitational-wave measurements reach sufficient precision.

## 31.6 Conclusion

In standard QFT, running couplings arise from loop corrections in continuous fields and are organized by the renormalization group, at the price of formal divergences and an incomplete treatment of gravity. In the Foam-Plexus framework, the same qualitative running behavior is recovered, but reinterpreted as the progressive activation of wormhole oscillator modes within each plexus. The Planck lattice provides

a natural ultraviolet cutoff: once all Planck-scale modes are active, running saturates, Landau poles disappear, and gravity avoids perturbative non-renormalizability.

This chapter is therefore a bridge between the continuum RG language familiar from QFT and the discrete statistical mechanics of the foam. It shows that the success of running-coupling phenomenology does not argue against a quantized spacetime; instead, it becomes one of the most direct experimental probes of how deeply we are beginning to resolve the wormhole plexus beneath the continuum.

# 32 Time and the Arrow of Time in the Foam–Plexus Model

## 32.1 Abstract

In Cassiopeia’s Foam–Plexus Theory of Everything, spacetime is a quantized lattice of quanta ( $N \sim 10^{99} \text{ cm}^{-3}$ ) connected by Planck-scale wormholes ( $\ell_P \sim 10^{-35} \text{ m}$ ). The foam itself is eternal and statistically time-symmetric at the Planck scale: wormhole formation and annihilation have no preferred direction. Time, as experienced by macroscopic observers, is not fundamental but *emergent*: it arises as a coarse-grained bookkeeping of wormhole oscillations, biased by the Gravity-Plexus and calibrated by the EM-Plexus. The electromagnetic plexus fixes the invariant signal speed  $c = 1/\sqrt{\varepsilon_0\mu_0}$ , while the Gravity-Plexus acts as the universal amplifier of wormhole density gradients, shaping proper time and curvature. The arrow of time emerges later, once stable polyhedral fermion loops condense and a small bias in perimeter-flow orientations produces the observed matter–antimatter asymmetry. Entropy then amplifies this microscopic bias into the macroscopic temporal arrow. This chapter unifies emergent time, relativistic time dilation, and the arrow of time within the Foam–Plexus framework.

## 32.2 Eternal Foam and the Question of Time

In classical mechanics, time is an external parameter; in General Relativity (GR), it is a coordinate within a smooth four-dimensional manifold. In both views, time is treated as primitive. Yet this leaves several puzzles:

- Why does only gravity appear to warp time while EM, Strong, and Weak interactions do not?
- Why is the speed of light  $c$  invariant in all inertial frames?
- Why did the early universe begin in such a low-entropy state?

The Foam–Plexus model starts from a different foundation. The underlying foam is an *eternal* lattice of spacetime quanta with number density  $N \sim 10^{99} \text{ cm}^{-3}$  and characteristic spacing  $\ell_P$ . These quanta are linked by transient wormholes, each modeled as a harmonic oscillator with discrete spectrum

$$E_n = \hbar\omega_0 \left(n + \frac{1}{2}\right), \quad \omega_0 \sim t_P^{-1} \sim 10^{43} \text{ s}^{-1}, \quad (32.1)$$

where  $t_P$  is the Planck time. Plexuses (Gravity, EM, Strong, Weak, Higgs) emerge as correlated subnetworks of wormholes with specific connectivity patterns.

At this deepest level, wormhole formation and annihilation,

$$w \longleftrightarrow \emptyset, \quad (32.2)$$

are statistically time-symmetric. There is no built-in temporal direction in the foam itself. Time, as an ordered sequence with a direction, must therefore emerge from higher-level structure: from plexus dynamics, coarse-graining, and loop condensation.

## 32.3 Wormhole Dynamics as the Basis of Time

### 32.3.1 Ticks from foam refresh cycles

Each wormhole configuration has a characteristic dwell time  $\tau \sim t_P$ . Causal propagation across the foam proceeds via stochastic hopping along transient wormholes; on large scales, this defines a coarse-grained *sequence* of events. In this sense, time intervals are nothing more than *counts of foam refresh cycles* along a path.

Let  $n$  be the expected number of wormhole refreshes along a coarse-grained trajectory between two events. Then the emergent time interval can be written as

$$\Delta t \sim n t_P, \quad (32.3)$$

with the detailed statistics encoded in the local connectivity of the foam.

In the continuum limit, this is summarized by a connectivity tensor  $C_{\mu\nu}(x)$ , constructed as a coarse-grained expectation over wormhole orientation vectors  $\mathbf{d}_w$ :

$$C_{\mu\nu}(x) \sim \langle d_w^\mu d_w^\nu \rangle_x. \quad (32.4)$$

The foam Laplacian  $\Delta_C$  built from  $C_{\mu\nu}$  replaces the continuum Laplacian  $\nabla^2$  and controls how excitations propagate. Proper time along a worldline is then the coarse-grained count of foam refresh events weighted by the local Gravity-Plexus contribution to  $C_{\mu\nu}$ .

### 32.3.2 Electromagnetic Plexus: fixing $c$

The EM-Plexus defines the invariant speed of causal signals by setting the effective permittivity and permeability of the foam:

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}. \quad (32.5)$$

In the Foam-Plexus model,  $\varepsilon_0$  and  $\mu_0$  are not fundamental constants of a background continuum but emergent bulk properties of the EM-Plexus—statistical measures of how EM wormhole modes propagate and couple.

Once the EM-Plexus has fully emerged and stabilized,  $c$  becomes rigid: all Plexuses must respect this speed-limit. Lorentz invariance arises from the isotropy of EM connectivity at large scales and the fact that all other Plexuses (Gravity, Weak, Strong, Higgs) propagate through the same foam substrate.

Before EM stabilization, however,  $\varepsilon_0$  and  $\mu_0$  are effectively undefined, and there is no fixed causal speed-limit. This provides a natural explanation for the extreme rapidity of inflation: the foam has a well-defined refresh time  $t_P$ , but the emergent value of  $c$  has not yet crystallized.

### 32.3.3 Gravity Plexus: shaping intervals

The Gravity-Plexus is special. It acts as the *universal amplifier* of random wormhole density, biasing the renewal of *all* Plexuses and defining the effective metric structure. A simplified form for the gravity-related wormhole density is

$$\rho_{w_g}(r) = \rho_0 + R_g \tau_g \frac{BM}{r} + \rho_{w_{g,\text{relic}}}(t), \quad (32.6)$$

where  $R_g$  is the gravity-side wormhole formation rate,  $\tau_g$  is a typical dwell time,  $B$  encodes geometry,  $M$  is mass, and  $\rho_{w_{g,\text{relic}}}$  contains long-lived relic loops that dilute with expansion:

$$\rho_{w_{g,\text{relic}}}(t) = f \rho_{w_g}(t_0) \left( \frac{a(t_0)}{a(t)} \right)^3, \quad f \sim 10^{-6} \text{ (galactic)}, \quad 10^{-9} \text{ (cosmic)}. \quad (32.7)$$

In regions of higher gravity-plexus density, effective foam paths between events are *shortened* in terms of refresh cycles; in regions of lower density, paths are *stretched*. The emergent proper time interval can be written schematically as

$$d\tau^2 \propto \frac{1}{\rho_{w_g}(x)} dt^2, \quad (32.8)$$

which in the continuum limit reproduces the usual GR relation

$$d\tau = \sqrt{g_{00}(x)} dt, \quad (32.9)$$

with  $g_{00}$  emerging from the coarse-grained Gravity-Plexus connectivity.

In this hierarchy:

- The EM-Plexus fixes the invariant speed  $c$ ,
- The Gravity-Plexus sculpts proper time intervals via wormhole density gradients,
- Other Plexuses (Weak, Strong, Higgs) largely appear “rigid” at macroscopic scales—they do not significantly alter the counting of foam refresh cycles along macroscopic worldlines.

This explains why *only* gravity is observed to warp time.

## 32.4 Planck-Scale Jitter and Observables

Because emergent time is built from finite, discrete refresh cycles, there is an irreducible stochastic component: *Planck-scale jitter*. In practice, this is hugely suppressed by coarse-graining over enormous numbers of wormholes, but it sets a fundamental floor on time resolution.

Potential observational consequences include:

- **Ultimate atomic clock stability:** at sufficiently high precision, clock phase may be limited by foam-induced fluctuations in the Gravity-Plexus, rather than technical noise.
- **Gravitational wave noise floor:** wormhole density fluctuations predict a background strain noise  $\Delta h/h \sim 10^{-5}$  at the foam level, which may appear as a stochastic floor in ultra-sensitive detectors.
- **Cosmological imprints:** early-time foam alignment and Gravity-Plexus fluctuations can seed subtle deviations in CMB anisotropy statistics, linked to the low-entropy initial conditions derived elsewhere.

## 32.5 Arrow of Time from Loop Orientation

### 32.5.1 Time-symmetric foam and oriented loops

At the foam level, wormhole processes are time-symmetric:

$$w \longleftrightarrow \emptyset \quad (32.10)$$

occurs with equal probability in either temporal direction. The foam by itself has no arrow of time.

An arrow emerges only when *stable polyhedral loops* condense. Fermions are modeled as tetrahedral (leptons) or pentahedral (quarks) loop structures with perimeter flux flows. The orientation of those perimeter fluxes defines particle vs. antiparticle states:

$$\psi_{\text{matter}} \equiv + \oint \vec{J} \cdot d\vec{\ell}, \quad \psi_{\text{antimatter}} \equiv - \oint \vec{J} \cdot d\vec{\ell}. \quad (32.11)$$

Reversing a loop's flux corresponds to exchanging matter and antimatter; it is the microscopic analogue of a time-reversal operation acting on the perimeter currents.

### 32.5.2 Primordial asymmetry and temporal bias

If loop orientations were perfectly symmetric, the universe would contain equal amounts of matter and antimatter, and no global temporal bias would arise. In the Foam-Plexus model, however, the condensation process is *slightly* biased in favor of baryonic (matter) loop orientations. The baryon asymmetry parameter,

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}, \quad (32.12)$$

is interpreted as a small but fundamental bias in loop orientation in the early universe.

Once this bias exists, the universe naturally evolves along the matter-dominated branch: matter loops survive and cluster, while antimatter loops largely annihilate away. The emergent temporal direction is then identified with the direction in which matter density increases from near-zero to its present value. In this picture, the arrow of time and the matter-antimatter asymmetry share a common geometric root: a tiny bias in perimeter-flow orientation within the foam.

### 32.5.3 Entropy as amplifier, not origin

Entropy does not *create* the arrow of time; it *magnifies* the microscopic orientation bias. Once a preferred branch has been selected by loop orientation (matter vs. antimatter), standard statistical mechanics ensures that:

- microscopic reversibility at the foam level,
- plus a slight macroscopic bias in initial conditions,

together drive entropy to increase along the matter-dominated branch.

This aligns with the low-entropy cosmology derived earlier: a rare region in the eternal foam experiences a sweet-spot collapse of wormhole lengths and an orientation bias in loop condensation. Inflation then stretches this tiny, low-entropy, matter-biased patch out to cosmic scales. The arrow of time we experience is the legacy of that early, local symmetry breaking.

## 32.6 Time Reversal vs. Time Travel

In formal physics, the time-reversal operator  $T$  acts as

$$t \mapsto -t, \quad \vec{v} \mapsto -\vec{v}, \quad \vec{J} \mapsto -\vec{J}. \quad (32.13)$$

In the Foam-Plexus model, this corresponds to reversing perimeter fluxes and exchanging matter loops with their antimatter counterparts. It is a *local* operation on loop configurations and foam currents.

What it does *not* do is reconstruct macroscopic histories or restore the universe to a previous low-entropy state. The global wormhole connectivity, the Gravity-Plexus density gradients, and the accumulated entropic structure are not undone by flipping local loop orientations. Time reversal in this sense is a change of microphysical orientation, not a cinematic rewind of lived experience.

This distinction dispels a common misconception: fundamental time-reversal symmetry (or its breaking) does not imply the possibility of traveling back to one's own past. The arrow of time is tied to a global orientation bias and entropic gradient, not to a reversible film of events.

## 32.7 Conclusion

In the Foam-Plexus model, time is an emergent property of wormhole dynamics in an eternal, time-symmetric foam. The EM-Plexus sets the invariant speed  $c$ , while the Gravity-Plexus—acting as the universal amplifier of wormhole density gradients—shapes proper time intervals and spacetime curvature. The arrow of time arises later, when stable polyhedral loops condense and a small bias in perimeter-flow orientations favors matter over antimatter. Entropy then amplifies this microscopic asymmetry into the macroscopic irreversible flow we observe.

This unifies several deep puzzles:

- why only gravity warps time,
- why  $c$  is invariant,
- why the early universe had low entropy, and
- why time has a preferred direction linked to matter-antimatter imbalance.

Time, in this view, is neither an illusion nor a primitive coordinate but a derived, foam-level statistic shaped by Plexus dynamics and loop topology.

# 33 Charge as Angular Momentum in the Foam–Plexus Model

## Overview

In the Foam–Plexus model, electric charge is reinterpreted as a manifestation of quantized angular momentum carried by perimeter flows on polyhedral fermion structures. Fermions emerge as tetrahedral (leptons) or pentahedral (quarks) wormhole–loop intersections, with each face supporting a closed, interaction–specific flux loop.

In this chapter we:

- define charge as an integer–quantized sum of perimeter angular momenta on the EM face,
- show how a tiny bias in primordial loop condensation produces the observed matter–antimatter asymmetry, and
- explain why proton and electron charges have exactly equal magnitude,  $|Q_p| = |Q_e|$ , as a global angular–momentum constraint on the foam.

This chapter is meant as an add–on refinement to the earlier Foam–Plexus discussion of the arrow of time and matter–antimatter asymmetry.

## 33.1 Fermions and Perimeter Flux in the Foam–Plexus Model

In the Foam–Plexus model, spacetime is a quantized lattice of discrete quanta connected by dynamic wormholes, forming overlapping subnetworks (plexuses) that mediate the fundamental interactions. Particles emerge as stable polyhedral intersections of wormhole loops, with perimeter fluxes on their edges defining interaction strengths and charges.

Fermions appear as:

- **Leptons:** Tetrahedra with faces corresponding to Gravity, Electromagnetic (EM), Weak, and Higgs interactions.
- **Quarks:** Pentahedra, adding a Color (QCD) face to the tetrahedral set.

Each face supports a closed wormhole loop; the edges of the polyhedron carry oriented flux segments. These perimeter flows are modeled as quantized angular momentum modes defined on the EM face of the polyhedron, and it is this structure that we identify with electric charge.

## 33.2 Charge as Quantized Perimeter Angular Momentum

We model each EM–relevant edge  $i$  of a fermion’s polyhedron as carrying a quantized angular momentum

$$L_i = n_i \hbar, \quad n_i \in \mathbb{Z}, \quad (33.1)$$

with the *sign* of  $n_i$  specifying the direction of the perimeter flow. The total EM–relevant angular momentum around the perimeter of the EM face is then

$$L_{\text{EM}} = \sum_{\text{edges } i \in \text{EM face}} L_i = \hbar \sum_{\text{edges } i \in \text{EM face}} n_i. \quad (33.2)$$

We define the electric charge  $Q$  of a fermion as a dimensionful multiple of this integer sum:

$$Q = e \sum_{\text{edges } i \in \text{EM face}} n_i, \quad (33.3)$$

where  $e$  is the elementary charge. In this picture:

- The *magnitude* of charge is set by the number and configuration of flux quanta on the EM face.
- The *sign* of charge is set by the net orientation (sign of the summed  $n_i$ ).

Antiparticles correspond to the same polyhedral geometry with all EM perimeter fluxes reversed:

$$n_i \longrightarrow -n_i \quad \forall i \in \text{EM face} \quad \Rightarrow \quad Q_{\bar{p}} = -Q_p. \quad (33.4)$$

More generally, charge conservation in any interaction is a direct consequence of total EM angular–momentum conservation in the perimeter loops:

$$\sum_{\text{initial}} Q_j = \sum_{\text{final}} Q_k \quad \Leftrightarrow \quad \sum_{\text{initial}} L_{\text{EM},j} = \sum_{\text{final}} L_{\text{EM},k}. \quad (33.5)$$

Fractional quark charges (e.g.  $+2/3e$  for up quarks,  $-1/3e$  for down quarks) arise from the specific combinatorics of  $n_i$  on the pentahedral EM face, but the fundamental unit  $e$  and its sign still follow from the integer sums in Eq. (33.3).

### 33.3 Biased Loop Condensation and Matter–Antimatter Asymmetry

In the early Foam–Plexus universe, the underlying quantum foam lattice produced wormhole loops with balanced positive and negative flux orientations. At the level of individual EM oscillators we have

$$\langle L \rangle = 0, \quad P(L) = P(-L), \quad (33.6)$$

reflecting an underlying time–reversal and charge–conjugation symmetry in the foam itself.

As plexuses stabilized and the system cooled, these loops began to condense into stable polyhedral structures. Following the arrow–of–time analysis elsewhere in this Add–On Part, we assume:

- Wormhole loops condense into tetrahedra and pentahedra with a *slight* bias favoring one orientation class over the other.
- This bias is tied to Weak–Higgs chirality: the alignment of Weak and Higgs faces makes it slightly more likely for certain EM perimeter orientations to survive as stable loops.

Concretely, we may define probabilities  $P_+$  and  $P_-$  for a given loop to condense into a stable matter–type polyhedron with net positive or negative EM flux. Matter–antimatter symmetry would require  $P_+ = P_-$ ; instead we assume a tiny but real bias

$$P_+ - P_- \equiv \delta P \sim 10^{-10}, \quad (33.7)$$

consistent with the observed baryon asymmetry parameter

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}. \quad (33.8)$$

In this picture:

- Antimatter is indeed produced in the early universe, with polyhedra whose perimeter fluxes are reversed relative to their matter counterparts.
- However, annihilation plus the tiny bias in condensation probabilities leaves a small residual surplus of matter polyhedra.

Negative–flux EM loops preferentially condense into lepton–like tetrahedra (e.g. electrons), while positive–flux loops preferentially condense into baryon–like pentahedra (e.g. protons and quarks). The detailed origin of the bias is tied to the Weak–Higgs chiral structure of the faces: the same geometric mechanism that enforces left–handedness of weak interactions for leptons also gives a small preference for one sign of perimeter angular momentum in the EM face.

### 33.4 Exact Proton–Electron Charge Equality

The crucial global constraint is that the foam, before condensation, has *zero* net EM angular momentum:

$$L_{\text{EM}}^{(\text{total, initial})} = 0 \quad \Rightarrow \quad \sum_{\text{all loops}} Q_{\text{loop}} = 0. \quad (33.9)$$

After condensation into fermionic polyhedra plus residual foam modes, this becomes

$$\sum_{\text{electrons}} Q_e + \sum_{\text{protons}} Q_p + Q_{\text{residual}} = 0. \quad (33.10)$$

Here:

- $\sum_{\text{electrons}} Q_e$  is the sum of all electron–like lepton charges,
- $\sum_{\text{protons}} Q_p$  is the sum of all proton (and baryon) charges,
- $Q_{\text{residual}}$  is the net charge stored in uncondensed EM loops and bosonic modes of the foam, which is expected to be *extremely* small on cosmic scales.

On large scales the universe is observed to be electrically neutral:

$$n_e \approx n_p, \quad \sum_{\text{visible}} Q \approx 0. \quad (33.11)$$

Inserting this into Eq. (33.10) and assuming  $|Q_{\text{residual}}| \ll n_e e$  forces

$$|Q_e| = |Q_p|. \quad (33.12)$$

Thus, once we assume:

1. an initially neutral foam with zero net EM angular momentum,
2. condensation into a universe that is electrically neutral on large scales, and
3. negligible residual net charge in uncondensed foam modes,

the *only* consistent solution is exact equality of proton and electron charges.

Compared to grand–unified or anomaly–based explanations, the Foam–Plexus mechanism is purely geometric and kinematic: it is the constraint that a neutral foam condensing into a neutral matter content must partition EM angular momentum into elementary building blocks whose charges match exactly. Fractional quark charges emerge from internal pentahedral combinatorics, but composite baryons sum to  $+e$ , balancing the electrons one–for–one.

### 33.5 Residual Foam Modes and Vacuum Energy

Not all EM perimeter flux condenses into fermionic polyhedra. Some fraction remains in:

- high–frequency EM plexus modes,
- bosonic double–loops lacking Gravity faces,
- and small, short–lived wormhole configurations in the foam.

These residual modes store EM–related energy and can be viewed as a component of vacuum energy.

However, in the Foam–Plexus model, double–loop bosons do not carry Gravity faces and therefore *do not source curvature*. Their energy contributes to the vacuum in the EM plexus but not to the Gravity plexus, helping to resolve the cosmological constant problem in the dark–energy sector (as discussed in the Dark Energy and Gravity–Plexus chapters of this Add–On Part).

From the charge–balance point of view, these residual modes carry at most a tiny net charge  $Q_{\text{residual}}$ , allowing Eq. (33.10) to enforce exact proton–electron charge equality while leaving most vacuum energy gravitationally inert.

## 33.6 Implications and Observational Signatures

Although this chapter is primarily structural and conceptual, several classes of observational signatures follow naturally.

### 33.6.1 Precision QED and $(g - 2)$

Small deviations from standard QED predictions may arise from:

- subleading contributions of residual EM foam modes, and
- subtle corrections to field propagators from polyhedral perimeter structure.

In practice, these would appear as tiny shifts in quantities such as the anomalous magnetic moments of the electron and muon,

$$\frac{\Delta(g - 2)}{(g - 2)} \lesssim 10^{-12}, \quad (33.13)$$

well below current experimental uncertainties but potentially within reach of future generations of  $(g - 2)$  experiments and ultra-precision spectroscopy.

### 33.6.2 Vacuum Birefringence and Foam Anisotropy

In strong EM fields, the detailed structure of EM plexus loops and their angular momentum content may induce tiny anisotropies in the propagation of polarized light, manifesting as an effective vacuum birefringence:

$$\Delta n \lesssim 10^{-6}, \quad (33.14)$$

for extreme field strengths (e.g. magnetars, high-intensity laser facilities). The Foam-Plexus model predicts a specific dependence of this effect on the local density of wormhole loops and the alignment of perimeter angular momentum, potentially distinguishable from pure QED predictions.

### 33.6.3 Ultra-Low-Frequency Backgrounds

Residual foam modes associated with large-scale rearrangements of EM and Gravity plexus structure may contribute to ultra-low-frequency backgrounds, for example in the pulsar-timing band:

$$f \sim 10^{-10} \text{ Hz}, \quad (33.15)$$

where long-wavelength stochastic variations in plexus connectivity could leave correlated timing signatures. While highly speculative, this offers a possible probe of the large-scale angular-momentum distribution in the foam.

### 33.6.4 Cosmological Constant and Charge Balance

Finally, the linkage between charge balance, residual foam modes, and bosons' lack of Gravity faces suggests a correlation between:

- the magnitude of the cosmological constant (or evolving dark-energy density), and
- the smallness of any net residual charge density in the universe.

In principle, improved constraints on cosmic charge neutrality and dark-energy evolution could jointly test this aspect of the Foam-Plexus picture.

## 33.7 Conclusion

Recasting electric charge as quantized angular momentum in perimeter wormhole loops provides a natural geometric foundation for charge conservation in the Foam-Plexus model. A tiny bias in primordial loop condensation, tied to Weak-Higgs chirality, explains the observed matter-antimatter asymmetry without requiring large-scale initial antimatter that later annihilates completely.

At the same time, the requirement that a neutral foam condense into a globally neutral universe enforces exact proton–electron charge equality: the net EM angular momentum of the foam must be partitioned into building blocks whose positive and negative charges match exactly. Residual EM–related foam modes store vacuum energy without gravitating, thanks to the absence of Gravity faces on bosonic double–loops, linking this charge–angular–momentum picture to the Foam–Plexus treatment of dark energy and the cosmological constant.

Taken together, these ingredients offer a unified, topological account of charge, matter–antimatter asymmetry, and proton–electron equality, and they naturally slot into the Add–On Part as a bridge between the micro–geometry of fermions and the macro–cosmological behavior of the Foam–Plexus universe.