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Article

Relative-Entropy Variational Principle for Semiclassical Gravity with Finite-Resolution Boundaries

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Abstract

We propose a causal-diamond formulation of semiclassical gravity in which a finite-resolution boundary regulator (Coherency Screen) supplies the minimal edge structure required for a local description in a Wheeler–DeWitt setting. Diamond-local dynamics are defined by an informational variational principle: for each diamond O , the effective cost functional is the relative entropy $S_{\text{rel}}(\rho_O || \sigma_O[g])$ between the reduced physical state and a geometric reference family. In the small-diamond modular/KMS regime, a derivative expansion of this cost (via heat-kernel spectral expansion) yields a local effective action whose leading terms recover the Einstein sector and select a spinorial (Dirac-type) transport structure. A discrete edge-mode counting, together with Newton's constant G , fixes a characteristic resolution scale $M_s \sim 3 \times 10^{13}$ GeV. Treating M_s as the onset of the leading stiffness correction places the high-curvature regime in a plateau universality class, giving a capacity-set scalar amplitude and a tensor target $r \sim 10^{-3}$. We further discuss how the same boundary logic constrains the gauge and mass sectors in a spectral-action-compatible formulation, suggesting discrete relations among effective coupling normalizations and a structured organization of charged-lepton scales via geometric accessibility of the boundary algebra. We also outline late-time phenomenological extensions in which finite-resolution boundaries induce a mild running of effective stiffness and horizon-set acceleration scales. The construction yields a compact set of correlated, falsifiable targets tied to a single microscopic resolution scale.

Keywords: semiclassical gravity; spectral action; relative entropy; causal diamonds; fine-structure constant; holographic boundary; edge modes; non-commutative geometry; holographic principle

1. Conceptual Foundations

We propose a boundary-register mechanism for relating quantum mechanics, gravity and gauge forces within a timeless Wheeler–DeWitt (WDW) framework [1]:

$$H\Psi = 0$$

where the global state Ψ is constrained rather than time-evolved. The operator H acts as a rigid constraint enforcing invariance under smooth coordinate transformations (diffeomorphism); physically, this implies that observables must be strictly relational and cannot depend on a background grid. In such a theory, dynamics cannot mean change of Ψ ; it must mean the appearance of consistent correlations (the perceived dynamics) accessible to an internal observer [2].

Before we list the formal rules, we outline our destination. The immediate operational task is to fix the discrete hardware required for local physics in a timeless, diffeomorphism-invariant setting. We focus on the causal diamond, treating its boundary not as an ideal smooth surface, but as a finite-resolution register (Coherency Screen) that stores the minimal edge data needed to define subsystems. We first establish that such a finite-capacity register must exist, and why this forces a channel-count description of gravitational stiffness [3]. We then derive the specific geometry of this hardware and the

unavoidable bookkeeping cost of representing smooth geometry on a digital boundary. Finally, we show how this topology fixes a unique channel multiplicity N and a unique microscopic energy scale M_s , thereby anchoring the macroscopic stiffness of gravity (Newton's constant G) to a fixed hardware basis. The outcome is a compact axiomatic framework that later sections will use without introducing new primitives.

1.1. Axiomatic Basis

We are not starting from a preferred lattice or a preferred field content; we are starting from what it takes to define a local observable at all: a causal region (P2), a boundary completion (P3), a modular clock (P4), a finite bandwidth (P5) and minimal isotropic connectivity (P7).

Axiom P1 (Non-factorization): The physical Hilbert space in gravity does not factorize across spatial subregions ($\mathcal{H} \neq \mathcal{H}_A \otimes \mathcal{H}_B$). This means local subsystems are not automatically defined as in ordinary QFT [4]. Spacetime cannot be sliced into independent subsystems without breaking the physical links that bind them.

Axiom P2 (Operational Locality): Local physics is organized by Causal Diamonds [5], the intersection of what an observer can influence and what can influence the observer. The region of operational access is a causal object, not a chosen slice. Because a signal must return to the register to be counted, the actual range of any measurement is limited to the area where a query-response loop can successfully close (Reciprocity).

Axiom P3 (Edge Completion / Local Algebra): A consistent subregion algebra requires Edge Modes (Extended Hilbert Space) [4,6] that restore factorization at the boundary. Edge completion introduces boundary center data that fixes gluing of interior/exterior algebras; these degrees of freedom are required to establish the notion of interiority (inside vs. outside).

Axiom P4 (Modular Locality): In the small-diamond limit, the vacuum satisfies the Kubo-Martin-Schwinger (KMS) condition with respect to a geometric modular Hamiltonian (the generator of modular flow) [7–9], implying local thermality and canonical modular flow near the boundary (local restriction generates a thermal horizon). Crucially, observers with finite lifetimes cannot resolve the full global topology of the state. Modular time acts as a Spectral Filter, ordering excitations by the geometry they can operationally explore (Hologonomy Barrier).

Axiom P5 (Finite Capacity): There exists a physical bandwidth limit, implemented as a stretched-horizon regulator $\delta = M_s^{-1}$ [10–12]. This regulator constrains the edge modes (Axiom P3) to a finite-resolution boundary register that encodes the interior reduced state (via edge completion); continuum descriptions cannot be extrapolated arbitrarily. Because the bulk is continuous while the screen is discrete, the horizon functions as an impedance matcher: bulk fields cannot couple perfectly to boundary pixels and generically pay a geometric transmission cost (contact resistance) to couple to the digital degrees of freedom.

Axiom P6 (Gauge Topology): Boundary charge sectors are described by the holographic correspondence between a bulk Chern-Simons topological field theory and a boundary Wess-Zumino-Witten (WZW) algebra (chiral boundary current algebra), characterized by an integer level $k \in \mathbb{Z}$ [13]. This ensures that gauge response is quantized by topological edge structure rather than continuous parameters.

Axiom P7 (Discrete Isotropy): Minimal isotropic spatial transport requires the signed Cartesian port set $\{\pm x, \pm y, \pm z\}$, implying coordination $z = 6$. Geometrically, this forces the local transport substrate to be octahedral (the dual of the cubic lattice), as it is the unique convex regular polyhedron with 6 vertices corresponding to these minimal directions.

1.2. Ontology and Screen Specification

Since the physical Hilbert space does not factorize under subregions (Axiom P1), any attempt to define a local subregion algebra requires boundary edge completion (Axiom P3) [4]. Therefore, once one insists on a local subregion algebra, a boundary register is not optional; it is the minimal data structure that makes interiority well-defined. This boundary completion is what we call the Coherency

Screen. Ontologically, it is the minimal boundary data that must be specified to say what it means for the region to be a subsystem.

With the necessity of the screen established, we now specify its operational structure, covering discretization, geometry and terminology.

Discretization

Axioms used: P4, P5. Standard field theory assumes infinite divisibility, which implies unbounded information density [14]. Under Axiom P5, this is not physically admissible. To satisfy Axiom P5, the edge modes must be stored on a register with finite resolution.

We implement this as a stretched-horizon regulator at proper distance δ from the bifurcation surface (maximal S^2 cross-section where the boundary geometry splits and modular time pivots) and define the coherency scale:

$$M_s \equiv \delta^{-1}, \quad L_s \equiv M_s^{-1}$$

Near the horizon, proper time and modular time are related by a redshift factor $t = \delta\tau$. Identifying the minimum resolvable proper time with the hardware scale ($t_{\min} \equiv \delta$) fixes the dimensionless modular cutoff:

$$\varepsilon \equiv \tau_{\min} = \frac{t_{\min}}{\delta} = 1$$

Setting $\varepsilon \neq 1$ would imply resolvable sub-pixel modular time, contradicting finite capacity.

Breadth vs. Depth

Following the requirement that the boundary must store the data defining the interior subsystem (Axiom P3) at finite resolution (Axiom P5), the screen is not a passive skin but an active register. Consequently, it must physically distinguish and update states when signals cross it. We call these updates null arrivals—field excitations traveling along light-like paths that intersect the causal diamond boundary. Since the resolution is finite, these arrivals define a discrete pixel tiling. The number of boundary pixels on the maximal S^2 cut of area A is called the breadth:

$$N_{\text{surf}} \equiv \frac{A}{L_s^2} = AM_s^2$$

Each spatial pixel hosts a local state register (Hilbert space) encoding multiple independent degrees of freedom (field types, spin states, charge sectors). We refer to this full information column as a deep pixel. The effective number of independent modes it contains is the channel multiplicity N (depth). Operationally, N counts the distinct edge sectors (distinguishable internal configurations) available to a single pixel. In practice, N is fixed by the topological budget; is not a tunable model parameter. Physically, these channels act as parallel structural elements: Just as cable stiffness depends on strand count, vacuum gravitational stiffness is proportional to N .

With the basic pixel unit defined (by Axioms P3 and P5), the remaining axioms shape the architecture: a container (Axiom P2), a router (Axiom P7) and a clock (Axiom P4).

First, the container is a Causal Diamond (Axiom P2). It is the operational region accessible to an observer: the intersection of future and past lightcones. It is bounded by a null surface (lightlike boundary) and has a maximal spacelike S^2 cross-section (the bifurcation surface) [5]. Within the diamond, the bulk is not a static block, but a bundle of causal trajectories (null rays) connecting input to output.

Second, the router is governed by Discrete Connectivity. Axioms used: P7. In three spatial dimensions ($d = 3$), minimal isotropic transport requires the signed basis $\{\pm x, \pm y, \pm z\}$. This defines a Minimal Isotropic Model where directions are closed under inversion and permutation (enforcing discrete rotational symmetry), implying coordination $z = 6$. Under Axiom P7, the octahedral port set is the unique minimal isotropic connectivity possible; the six vertices are therefore forced as signal ports, the minimal isotropic junctions through which discrete causal transport proceeds. This discretization

fixes the natural unit ball of the register metric. A smooth continuum uses the L_2 norm (sphere) with spherical symmetry. A step-counting register uses the L_1 norm (octahedron), corresponding to step-counting geometry. Intuitively, the bulk wants to be a sphere (Lorentz symmetry), but the register can only be a digital octahedron. This L_1 vs L_2 mismatch will reappear later as the cost of digitization at the diamond tips (defined in §1.4).

Third, the clock is defined by modular periodicity. Axioms used: P4. In the small-diamond limit, the vacuum restricted to a wedge is KMS [8]. This supplies a canonical local clock: the modular flow acts as a dimensionless rotation with a natural cycle of 2π .

Deep Pixel as Collimator

Finite bandwidth implies aliasing: any bulk continuum description below L_s is a reconstruction [15]. Operationally, the screen behaves like a Shannon-Nyquist Low-Pass Filter: microstates differing only below L_s are physically indistinguishable. We therefore interpret each deep pixel as a collimator (directional filter, coherency aperture): it filters microscopic vacuum jitter into coherent causal rays. Operationally, as we will see in the [Appendices](#), the screen is an active element: it rectifies microscopic jitter into a stable signal. It does not merely store data; it converts random quantum noise into clear, distinguishable geometry (enforcing normalization).

Internal Phase Space

Beyond simple capacity, the screen requires a robust codebook to store orientation and phase information. Motivated by the local octahedral cell, we adopt a register with eight independent sectors, spanning an 8-dimensional phase space, where the mathematically optimal packing is a E_8 lattice [16]. To model accessibility, we partition these degrees of freedom into observable spatial base ($d = 3$) and internal phase fiber ($d = 5$), or $S^3 \times S^5$. This treats the vacuum as an E_8 information crystal purely for coding efficiency, maximizing information density (bits of distinguishability) per capacity [17], without making any gauge-unification claim.

This internal register language aligns naturally with spectral methods [18]. Let $\mathcal{A}$ denote the boundary-completed local observable algebra of the diamond (the subregion algebra after edge completion). Matter sectors can be described by the spectral accessibility of this algebra, quantified by a heat trace and an accessible phase-space volume of the accessible invariant manifold:

$$Z_{\mathcal{A}}(s) = \text{Tr } e^{-s\Delta_{\mathcal{A}}}, \quad \Omega_{\mathcal{A}} \equiv \lim_{s \rightarrow \infty} \frac{\text{Vol}(\mathcal{A})}{Z_{\mathcal{A}}(s)}$$

where $\Delta_{\mathcal{A}}$ is the Laplacian. Noncommutative Geometry (NCG) [19,20] will enter later as an operator-theoretic scaffold for gauge/matter transport; it is not required now for the topological budget itself.

Consequently, the physical mass of a particle is not a primitive parameter, but an entropic localization cost, or more concretely the minimal energy required to stabilize one bit of encoded information against modular noise [21]. The lepton construction ([Appendix D](#)) uses the operational law $\mathbf{m} : \propto 1/\Omega$ with lifetime-limited modular exploration to select its accessibility regimes (Volume/Tangent/Fiber) in strict correspondence with the three canonical definitions (Manifold G , Algebra $\mathfrak{g}$, Torus T) of the Lie group associated with the register phase space.

1.3. Entropic Principle: Action as Distinguishability

Because the screen is a finite-resolution register, the natural action principle is informational: how distinguishable the physical boundary state is from a geometric reference family. We define the coherency cost as the relative entropy between ρ_O (fixed by Ψ) and $\sigma_O[g]$ (a semiclassical reference):

$$I_{\text{eff}} \sim S_{\text{rel}}(\rho_O \| \sigma_O) = \text{Tr}(\rho_O \ln \rho_O - \rho_O \ln \sigma_O) \geq 0$$

Intuitively, relative entropy is a model selection penalty representing the cost of telling states apart: minimizing it selects the simplest geometric reference that makes the physical state least surprising.

In the Rindler limit (near-horizon regime approximated as flat spacetime seen by an accelerated observer) [9], the vacuum satisfies the KMS condition (thermal equilibrium) [8] with respect to modular flow, so $\sigma_O \propto e^{-K_O}$ and relative entropy decomposes as $\Delta\langle K_O \rangle - \Delta S$. Near equilibrium, the Entanglement First Law [22,23] cancels linear variations and ensures the leading nontrivial cost is quadratic, controlled by local modular Hamiltonians. This is consistent with entanglement-equilibrium routes to Einstein-like dynamics [24].

Lemma (Fixed Container)

Since ρ_O is held fixed while $\sigma_O[g]$ is varied, the capacity of the container must be fixed upstream; otherwise the variational family would not live on a fixed space. The channel multiplicity N must thus be determined by the topology of the screen alone.

1.4. Topological Budget: Deriving the Channel Multiplicity N

We now determine the precise channel multiplicity N by summing the information costs of the geometric features mandated by our axioms.

Additivity

Entropy adds across independent contributions ($S_{\text{tot}} = S_1 + S_2$), while state counts multiply ($N_{\text{tot}} = N_1 N_2$). We therefore build the vacuum capacity as an additive topological action S_{vac} and then define $N \equiv \exp(S_{\text{vac}})$. Physically, N represents the effective channel multiplicity (in the Shannon/thermodynamic sense) of the boundary register.

Bulk Baseline

Axioms used: P2 (+ Hadwiger minimality [25]). From Axiom P2, the interaction boundary for a local observer is the diamond bifurcation surface (S^2). We require a scale-free diffeomorphism-invariant functional on that cut. We adopt the Euler characteristic—identified by Hadwiger’s theorem as the unique scale-free, continuous, motion-invariant additive valuation on convex bodies—as the minimal topological generator on the S^2 cut. On smooth manifolds, the Euler characteristic is diffeomorphism invariant and is represented by Gauss–Bonnet [26]:

$$S_{\text{bulk}} \equiv \oint_{S^2} R^{(2)} dA = 4\pi\chi(S^2) = 8\pi$$

Physically, this doubling relative to the standard spatial curvature integral (4π) aligns with the Causal Diamond structure nicely, reflecting that the topological invariant must capture the complete interaction boundary (the full sphere) rather than just a spatial cross-section.

Tip Regulator

Axioms used: P4, P7. The causal diamond has tips where the light rays forming its boundary converge (null generators) [27]. In a discrete register, a tip is a routing junction. The tip is therefore where the cost of digitization appears: the irreducible overhead required to represent a smooth L_2 manifold (spherical semiclassical flow) on a discrete L_1 transport substrate (octahedral register). We fix the minimal tip term Δ_{tip} using the minimal octahedral triangulation model compatible with $z = 6$ ports (Axiom P7).

Guided by Axioms P4 and P7, we set the junction overhead to the irreducible minimum, i.e., one unit of action distributed across the three transport axes per modular cycle (2π). This fixes Δ_{tip} :

$$\Delta_{\text{tip}} = \frac{1}{3 \times 2\pi} = \frac{1}{6\pi}$$

This value is independently confirmed by the Regge deficit [28]. The sum of angles is $4 \times (\pi/3) = 4\pi/3$. The curvature is concentrated at the tip as a deficit angle $\delta_{def} = 2\pi - \frac{4\pi}{3} = \frac{2\pi}{3}$. Distributing this deficit over the squared modular phase measure $(2\pi)^2$ notably yields the same result:

$$\kappa \equiv \frac{\delta_{def}}{(2\pi)^2} = \frac{2\pi/3}{4\pi^2} = \frac{1}{6\pi} \equiv \Delta_{tip}$$

We use $\kappa \equiv \Delta_{tip}$ as the same dimensionless tip impedance factor.

The same tip impedance $\kappa = 1/(6\pi)$ will reappear in the cosmological sector (Appendix A) as the leakrate that sets the duration of the coherent (inflationary) phase and, later, as a threshold for when the transmissive efficiency of the screen begins to drift at late times.

The Regge picture is not an independent axiom; it is an equivalent geometric representative of the same L_2 -on- L_1 mismatch forced by Axiom P7. Cost means extra bookkeeping capacity, not reduction in capacity. The screen must allocate additional edge labels to represent a junction on a discrete router while maintaining smooth modular flow. This is why Δ_{tip} enters additively in S_{vac} .

Global Defect Budget

Axioms used: P7 + Δ_{tip} . Once a per-port tip cost exists, the total defect budget per cell is forced by discrete isotropy ($z = 6$). Identifying the persistent defects of the boundary register with bulk matter content [29], the aggregate defect cost becomes:

$$\Omega_m \equiv z \Delta_{tip} = 6 \cdot \frac{1}{6\pi} = \frac{1}{\pi} \approx 0.318$$

Matter is not something added to the screen; it is the cost of building the screen itself. Because the register is discrete, it requires junctions to stitch the geometry together. We perceive these unavoidable topological defects as matter.

Fermionic Completion (Twist)

A register that encodes only bosonic orientation data is incomplete in a universe with fermions. To support a local spinor description, the boundary completion must include the minimal $\mathbb{Z}_2$ data associated with fermionic sign (spin structure), implemented here as a $\mathbb{Z}_2$ twist sector in the Orientation Register (Ising-type [30]) acting as the necessary topological branch point. The twist field σ carries quantum dimension $d_\sigma = \sqrt{2}$, reflected by the Ising fusion rule $\sigma \times \sigma = 1 + \psi$ (two possible fusion outcomes). This $\sqrt{2}$ is not a literal local Hilbert-space dimension; it is the standard non-integer quantum dimension measuring the asymptotic growth of the defect fusion space, and therefore contributes multiplicatively to the effective channel multiplicity (additive entropy $S_{twist} = \ln \sqrt{2}$). This is the minimal fermionic completion; higher defect sectors (e.g., parafermions) would imply supraminimal non-Abelian complexity [31].

Master Equation

We now add the three contributions to obtain the total channel capacity N :

$$S_{vac} = S_{bulk} + \Delta_{tip} + S_{twist} = 8\pi + \frac{1}{6\pi} + \ln \sqrt{2}$$

Exponentiating yields the channel multiplicity:

$$N = \sqrt{2} \exp\left(8\pi + \frac{1}{6\pi}\right) \approx 1.226 \times 10^{11}$$

We interpret N as the effective channel multiplicity (Hilbert-space multiplicity) per pixel (effective number of distinguishable states in the Shannon/thermodynamic sense) so it needs not be an integer. These degrees of freedom are localized at the boundary scale M_s and do not introduce additional light

propagating fields in the infrared. Given Axioms P1–P7 and our stated minimality conventions, the master equation is the unique minimal completion of the screen budget.

1.5. Discretizing Stiffness and Calibration

With the local hardware fixed by Axioms P1–P5, the boundary carries the interior data within a finite channel structure. We must now link this discrete hardware to the macroscopic stiffness of spacetime ($M_P^2 \propto 1/G$). Since the screen is the physical medium, stiffness is not an arbitrary parameter, but a constitutive property of the channel bundle itself. Thus, we discretize capacity, not spacetime. With the effective capacity $N_{\text{eff}} = \kappa N$ fixed upstream, we calibrate the single-channel bandwidth M_s by matching the resulting stiffness to the measured Newton constant G .

Constitutive Relation

Axioms used: P5 + extensivity of linear response. In the Einstein–Hilbert action [15], the coefficient of curvature is the inverse gravitational constant. Gravity is weak not because the coupling is small, but because the load is shared across massive parallelism [3,32]. Axiom P5 fixes the per-channel intensive spectral bandwidth M_s (UV cutoff frequency per strand, fixed by the horizon resolution $\delta = M_s^{-1}$). However, the macroscopic stiffness depends on the total extensive multiplicity N .

The remaining question is how many such channels contribute in parallel to the macroscopic stiffness M_P^2 . We distinguish raw multiplicity N from effective stiffness multiplicity N_{eff} by applying the geometric tip factor κ . We define $N_{\text{eff}} \equiv \kappa N$, where $\kappa \equiv \Delta_{\text{tip}} = 1/6\pi$. The constitutive stiffness law is then:

$$M_P^2 = N_{\text{eff}} M_s^2 = (\kappa N) M_s^2$$

M_P represents the aggregate response of the screen, while M_s is the single-channel bandwidth.

Numerical Calibration from G

We calibrate the bandwidth using the measured Newton constant G , expressed as the reduced Planck mass $M_P \equiv (8\pi G)^{-1/2} \simeq 2.435 \times 10^{18} \text{ GeV}$. Using the derived capacity N and efficiency κ , we solve for the unique bandwidth scale:

$$M_s = \frac{M_P}{\sqrt{\kappa N}} \approx 3.02 \times 10^{13} \text{ GeV}$$

Pixel energy budget

With the hardware scale fixed, we define the unitary pixel energy budget E_{pix} . Per the Fermionic completion defined earlier, the addressable payload count is $n_{\text{ch}} = N/\sqrt{2}$. We divide by the twist-sector dimension ($\sqrt{2}$) because it represents structural overhead rather than a data-carrying channel. Since susceptibility is additive over independent channels, maximum-entropy allocation implies a uniform budget:

$$E_{\text{pix}} \equiv \frac{M_s}{n_{\text{ch}}}$$

This value sets the saturation scale for the electroweak sector (Appendix C) and serves as the energetic anchor for heavy, short-lived excitations that fail to equilibrate with the hadronic vacuum (Appendix D).

Separation of Scales

We emphasize a strict separation of scaling: We distinguish extensive gravitational stiffness (scales with N_{eff}) from intensive gauge susceptibility (set by coherent coupling). Dimensionless gauge couplings are not multiplied by the macroscopic depth N . Operationally, the inverse coupling is

defined as a Fisher-information (Kubo–Mori) susceptibility [7,33] with respect to a chemical-potential deformation by a conserved boundary charge:

$$\alpha^{-1} \equiv \chi_{\text{tot}} \equiv \left. \frac{d^2}{d\lambda^2} S_{\text{rel}}(\rho_\lambda \| \rho_0) \right|_{\lambda=0}$$

This definition operationalizes the screen as a thermal crystal: local modular noise (intrinsic vacuum fluctuations) produces a universal per-pixel response, while macroscopic normalization is obtained by coherent summation dictated by screen connectivity:

$$\alpha^{-1}(M_s) = \Omega_{\text{coh}} \chi_{\text{pix}}$$

where χ_{pix} is the per-pixel modular susceptibility of the edge algebra and Ω_{coh} is fixed by S^2 flux normalization. This becomes consistent with Standard Model values when the WZW level k (Axiom P6) takes integer values.

The constitutive law implies a length dual:

$$L_P = \frac{L_s}{\sqrt{N_{\text{eff}}}}$$

The Planck length is thus a virtual resolution: it is the scale one infers by incorrectly assuming the vacuum stiffness arises from a single continuous field. In the screen ontology, the physically real resolution is L_s , while L_P is a derived effective scale set by parallelization.

Thermodynamic License: Recovering S_{BH} with Finite Resolution

Consistency with Bekenstein–Hawking entropy [34,35] is preserved. A horizon of area A contains $N_{\text{surf}} = A/L_s^2$ deep pixels and each deep pixel contributes an effective stiffness depth N_{eff} . The Bekenstein–Hawking form reappears as:

$$S_{\text{BH}} = \left(\frac{2\pi}{\ln 2} \right) N_{\text{surf}} N_{\text{eff}} \approx 10^{122} \text{ bits}$$

This result acts as a strong calibration and consistency check, granting the framework the thermodynamic license to function. It demonstrates that coarsening the vacuum geometry to a finite scale L_s (thereby curing UV divergences) does not delete the information required by black-hole thermodynamics; instead, it relocates it. We recover the standard horizon capacity in standard form as Surface $\times$ Depth, shifting the degrees of freedom from an ultra-fine surface tiling (L_P) to the massive depth of the internal registers (N_{eff}). This validates our central ontological shift: L_P is revealed as a virtual stiffness scale driven by parallelization, while L_s remains the physically real hardware resolution.

1.6. Heuristic Correspondences

The scaling relationships derived here mirror structures in established high-energy frameworks: **High-Energy Phenomenology:** The derived $M_s \sim 10^{13}$ GeV lies near scales often associated with the Type-I seesaw for neutrino masses [36,37] and with the characteristic mass scale of plateau inflation (Starobinsky scalaron) [38]. While phenomenological arguments single out this scale for distinct reasons, our framework naturally locates its unique bandwidth limit in the same range.

Large-N Gravity [32]: The scaling $M_p^2 \sim NM_s^2$ structurally realizes the Species Bound logic, where the Planck scale is renormalized by the number of active species.

Noncommutative Geometry (NCG) [20]: The screen functions as a finite-bandwidth register where M_s serves as the physical saturation limit.

String Theory: The impedance $\kappa = 1/6\pi$ shares the normalization structure of string amplitudes through the identity $\kappa = [\Gamma(4) \Gamma(1/2)^2]^{-1} = 1/6\pi$.

1.7. Emergent Time

If the fundamental hardware is a Wheeler–DeWitt state ($H\Psi = 0$), time cannot be a background parameter. In our framework, time is an emergent correlation between subsystems. We adopt the Page–Wootters mechanism [2], tailored to globally constrained states: apparent evolution arises from conditioning on an internal clock.

Axioms used: $H\Psi = 0$ and Axiom P4 (Modular Locality) in the small-diamond regime.

We partition the total Hilbert space into a clock subsystem C and the remainder R ,

$$\mathcal{H}_{\text{total}} = \mathcal{H}_C \otimes \mathcal{H}_R$$

and represent the global state as $|\Psi\rangle$. Although $|\Psi\rangle$ is static, an internal observer describes the conditional state of R given a clock reading t as:

$$|\psi(t)\rangle_R = \langle t|_C |\Psi\rangle$$

In the screen ontology, a physical clock is not an external device; it is any sufficiently coarse-grained subsystem with stable (approximately orthogonal) pointer states $|t\rangle_C$.

In the small-diamond (local Rindler/KMS) regime [24], the reference state is thermal with respect to the modular Hamiltonian K_O . In this regime, the natural clock choice aligns with modular flow. Although the screen microstructure is discrete at M_s , macroscopic clocks have dense spectra; consequently, discrete causal updates average into an effectively continuous parameter t at observational scales.

Semiclassical Wheeler–DeWitt solutions admit a Wentzel–Kramers–Brillouin (WKB) form [1],

$$\Psi[g] \approx \mathcal{A}[g] e^{iS_{\text{eff}}[g]}$$

This approximation bridges the quantum and classical worlds: just as light rays emerge from light waves, a distinct history of spacetime emerges from the quantum state wherever the phase S_{eff} changes rapidly.

We propose that, in the regime where modular flow is geometric, this phase functional S_{eff} is controlled by the same coherency principle introduced above (relative-entropy stationarity). The universe is timeless at the level of the global constraint, but dynamical at the level of conditional correlations accessible to an internal observer. The screen supplies both the bookkeeping needed for locality and the natural modular clock needed for ordering correlations. Time is not imposed on the theory; it is read out from the register.

With the hardware now fixed $(N, \kappa, M_s, \epsilon)$, the remaining results are no longer adjustable inputs but constrained outputs: Chapter 2 derives local dynamics from stationarity of relative entropy, while subsequent modules test the same screen constants across early-universe, gauge and mass sectors.

1.8. Parametric Closure and Consistency

Remarkably, this calibration leaves the model with no adjustable continuous parameters beyond G . With the screen topology fixing the dimensionless hardware (N, κ, ϵ) and G fixing the single bandwidth scale M_s , the remaining sectors are no longer adjustable inputs but correlated consequences of the same boundary register.

This unification works because the screen architecture is rigid. Causal diamonds define the local algebra, modular locality provides the clock, and finite resolution makes the energy cutoff physical. Relative entropy then selects the optimal geometry, while boundary topology enforces discrete normalization rules. In Chapter 2, we will use this fixed hardware to derive local dynamics, generating the standard Einstein and gauge sectors from a controlled small-diamond expansion.

Ultimately, different observables just probe different regimes of this single system: primordial saturation (Appendix A), gauge couplings (Appendix B), mass generation (Appendix C) and lepton spectra (Appendix D), extending to late-time cosmology (Appendix E).

2. Coherency Action and Dynamics

With the static screen architecture established in Chapter 1, we now define dynamics not as the time-evolution of Ψ , but as the emergence of effective laws governing accessible correlations. This reverses the standard order: the reduced boundary state ρ_O is the primary data, and geometry enters as the optimal reference description of that information.

In this view, the screen provides an effective boundary description of the region: coarse-grained geometry summarizes the net response of microscopic quantum fluctuations under the fixed cutoff and boundary algebra. Just as hydrodynamics replaces microscopic collisions with constitutive laws, the coherency framework replaces standard QFT loop summations with a controlled effective action organized by boundary structure and topology.

We implement this by using relative entropy as the diamond-local cost functional and defining dynamics by stationarity with respect to the geometric reference family.

Concretely, we treat dynamics as inference: given a fixed reduced boundary state ρ_O , we choose a semiclassical reference model $\sigma_O[g]$ that best matches it. S_{rel} is the natural mismatch functional because it is both an information-theoretic divergence (extra description length when using the wrong model) and a thermodynamic free-energy-like object in the KMS (Kubo–Martin–Schwinger equilibrium) setting [7,39–41] (the vacuum restricted to a small diamond being thermal with respect to modular flow).

Geometry $g_{\mu\nu}$ is not treated here as a fundamental field to quantize, but as the most economical description of boundary correlations compatible with the screen. This adopts the entanglement-gravity insight that spacetime response is governed by modular structure and entanglement equilibrium rather than independent field evolution [22–24,42,43].

We encode this principle in the coherency action:

$$S_{\text{coh}}[g; O] := S_{\text{rel}}(\rho_O \parallel \sigma_O[g]).$$

We then define local dynamics by stationarity with respect to the geometric data entering $\sigma_O[g]$. This construction is local and begins in the small-diamond regime, where modular flow is geometric (Bisognano–Wichmann/Unruh limit [8,9]). Subleading corrections are organized as a derivative expansion, as in Effective Field Theory [15]. The result is a coarse-grained local action:

$$S_{\text{eff}} = \int d^4x \mathcal{L}_{\text{coh}}.$$

Here $\mathcal{L}_{\text{coh}}$ is the local coherency Lagrangian density (coarse-grained relative-entropy cost per unit four-volume).

2.1. Variational Protocol

The key now is to prevent the usual ambiguity of varying geometry in entanglement-based gravity: in the screen ontology, the state space is fixed by the architecture.

Concretely, the container O (the causal diamond) is fixed by operational locality (Axiom P2). The algebra $\mathcal{A}$ is fixed by edge completion (Axioms P1–P3) [4,6]. The regulator is fixed physically at $\delta = L_s = M_s^{-1}$ and $\varepsilon = 1$ (Axioms P4–P5) [10,11]. Finally, the data ρ_O is fixed as reduced physical state determined by the global constraint.

What is varied is only the reference family $\sigma_O[g]$. In the small-diamond regime, where modular flow is geometric, the reference has the KMS form

$$\sigma_O[g] \propto e^{-K_O[g]},$$

so varying g is operationally varying the modular generator $K_O[g]$ at fixed cutoff and fixed boundary algebra $\mathcal{A}$ [8,9].

The distinction between extensive and intensive sectors is a structural necessity of the register ontology and explains the vast hierarchy between gravitational and particle scales. Gravity represents the aggregate stiffness of the entire channel bundle [3]; it is extensive because the dimensionful Planck scale ($M_P^2 = N_{\text{eff}} M_s^2$) sums the tension of N_{eff} parallel strands. Conversely, gauge response represents the local phase susceptibility of the pixels themselves; it is intensive because it measures the internal coordination of the transport protocol, independent of the total bundle depth. This architectural split ensures that while the Planck scale grows with the screen's total capacity, gauge couplings remain order-unity, reflecting the screen's internal phase-coherence rather than its aggregate size.

2.2. Entropic Action Principle

We now derive the gravitational response by requiring the reference model to be indistinguishable from the boundary data at the lowest energy scale. This treats Einstein's equations not as an assumption, but as the unavoidable equilibrium condition of a system attempting to match its internal geometry to its external correlations. Relative entropy S_{rel} decomposes into modular energy minus entanglement entropy [40]:

$$S_{\text{rel}}(\rho_O \parallel \sigma_O) = \Delta\langle K_O \rangle - \Delta S,$$

with $\Delta\langle K_O \rangle = \text{Tr}(\rho_O K_O) - \text{Tr}(\sigma_O K_O)$ and $\Delta S = S(\rho_O) - S(\sigma_O)$.

For perturbations around the reference vacuum, the first law of entanglement applies [22,23]:

$$\delta S = \delta\langle K_O \rangle.$$

Linear variations cancel, so the leading nontrivial contribution is quadratic. Imposing stationarity $\delta_g S_{\text{coh}} = 0$ enforces Einsteinian linear response at leading derivative order, consistent with entanglement-equilibrium derivations of the Einstein equation of state [24,43].

The screen sees ρ_O . Among all geometric models $\sigma_O[g]$, the one that makes the screen least surprised is what the screen calls spacetime. At lowest order, that rule obviously reduces to Einstein.

2.3. Spectral EFT Representation

We now move from the abstract entropic principle to a concrete spectral Effective Field Theory (EFT) representation in order to organize the higher-order corrections and make the local operator content explicit.

Inspired by spectral-action logic [18,44], this approach represents the coherency cost as a spectral trace, providing a controlled way to bridge information-theoretical cost and physical field theory [45]:

$$S_{\text{coh}} \approx \text{Tr} f \left(\frac{D_{\mathcal{A}}^2}{M_s^2} \right)$$

where $D_{\mathcal{A}}$ is a Dirac-type operator encoding metric and connection data on the boundary-completed structure, and f is a smooth aperture suppressing modes above M_s .

Applying the heat-kernel expansion [46,47] gives the standard local series:

$$\text{Tr} f(D_{\mathcal{A}}^2/M_s^2) \sim \int d^4x \sqrt{-g} [c_0 M_s^4 + c_2 M_s^2 R + c_F F_{\mu\nu}^2 + c_{R^2} R^2 + c_W W^2 + c_E E_4 + \dots].$$

The scaling split of Chapter 1 now becomes a reading rule:

Extensive sector (gravity): $M_P^2 = N_{\text{eff}} M_s^2$, $N_{\text{eff}} = \kappa N$.

Intensive sector (gauge): $\alpha^{-1}(M_s) = \Omega_{\text{coh}} \chi_{\text{pix}}$.

Ω_{coh} is the coherent normalization dictated by the screen connectivity and the S^2 flux measure.

Each pixel carries a boundary-completed edge sector. This cleanly separates two physical roles: gravity is an extensive stiffness that grows with channel count, while gauge response is an intensive

susceptibility set locally (with coherent normalization). Continuum descriptions often blur this distinction, but the screen architecture keeps it separate by construction.

2.4. Matter and Gauge Forces

Geometry specifies connectivity (router), matter is the payload and gauge fields enforce phase coherence during transport.

The $\mathbb{Z}_2$ twist sector fixed in [Chapter 1](#) implies that the payload is spinorial. The minimal coherence-preserving transport operator for a spinorial payload is first order, selecting Dirac transport as the leading local protocol:

$$S_{\text{matter}} = \int d^4x \sqrt{-g} \bar{\psi} (i\gamma^\mu D_\mu - m) \psi,$$

$$D_\mu = \partial_\mu + \frac{1}{4} \omega_\mu^{ab} \gamma_{ab} - iA_\mu.$$

This viewpoint is aligned with information-processing derivations of the Dirac structure [\[48\]](#) and with spectral constructions where transport is encoded by Dirac-type operators [\[19,20\]](#).

We then define the inverse coupling as the Kubo-Mori (Fisher information) [\[7,33\]](#) curvature of S_{rel} under a chemical-potential deformation $\rho_\lambda \propto e^{-(K_0 - \lambda Q)}$ of the boundary state by a conserved boundary charge Q :

$$\alpha^{-1} \equiv \chi_{\text{tot}} = \left. \frac{d^2}{d\lambda^2} S_{\text{rel}}(\rho_\lambda \parallel \rho_0) \right|_{\lambda=0}, \alpha^{-1}(M_s) = \Omega_{\text{coh}} \chi_{\text{pix}}.$$

For a Wess–Zumino–Witten (WZW) edge current algebra (the chiral boundary CFT induced by a bulk Chern–Simons sector) at integer level $k \in \mathbb{Z}$ (the quantized normalization fixed by gauge invariance) [\[30,49\]](#), the universal modular kernel is $\sin^{-2}(\tau/2)$. With modular time $\tau \in [\varepsilon, 2\pi - \varepsilon]$ and $\varepsilon = 1$, this gives:

$$\chi_{\text{pix}} = \frac{k}{4} \int_1^{2\pi-1} \frac{d\tau}{\sin^2(\tau/2)} = \frac{k}{4} (4 \cot(1/2)) = k \cot(1/2).$$

$\cot(1/2)$ is not a fitted numerology hook; it is the finite modular history of edge fluctuations around the KMS circle under the physical cutoff $\varepsilon = 1$. It represents the local, microscopic thermal noise unit of the screen. Its geometric origin is the regulated modular loop integral itself.

Remarkably, when this modular history is integrated with the lattice coordination factor Ω_{coh} , the value of gauge coupling $\alpha(M_s)$ is fixed to multiple significant digits ([Appendix B](#)). By identifying the specific integer level k of the boundary algebra, the theory derives force strengths as a direct consequence of thermal noise rather than using adjustable parameters.

This micro–macro step acts as a structural consistency check: if the boundary were just a random pixel gas, local modular correlators would not assemble into a clean global normalization. Instead, the screen requires rigid coordination so that local modular noise sums coherently into a smooth macroscopic response. This is the dynamical payoff of the [Chapter 1](#) screen architecture (causal region, boundary completion, modular clock, finite bandwidth, minimal isotropic connectivity), where the vacuum acts as an active rectifier of fluctuations [\[8,9,39\]](#). It also motivates the crystalline/impedance language used later, where exceptional-lattice rigidity offers a concrete model for this coherent summation [\[50\]](#).

2.5. Saturation Plateau

A continuum EFT can push curvature arbitrarily high by adding operators. A finite-bandwidth register cannot. As such, when curvature approaches M_s^2 , the screen cannot represent finer gradients and response must flatten. The minimal saturation closure activates the first subleading stiffness mode, representing the simplest plateau class [\[38,51\]](#):

$$\mathcal{L}_{\text{sat}} \sim R + \lambda R^2,$$

Since $M_P^2 = N_{\text{eff}} M_s^2$ is fixed and the R^2 stiffness scales with N_{eff} , a locking statement follows:

$$\frac{\lambda}{M_P^2} \sim \frac{1}{M_s^2}, \lambda = \frac{N_{\text{eff}}}{12} \Rightarrow \frac{2\lambda}{M_P^2} = \frac{1}{6M_s^2}.$$

This is another screen-only insight: in a generic continuum EFT, M_P and the higher-derivative onset scale are independent parameters; here, finite bandwidth forces them to lock.

2.6. Recovery of Standard Limits

The screen follows a single rule: minimize the coherency cost at fixed hardware. In the low-curvature regime this selects Einstein as the best geometric fit to the boundary data, while for frozen geometry it selects Dirac/Yang–Mills as the minimal coherence-preserving transport of the payload.

To see this unification, we can combine the spectral expansion into a single hardware-level action, which describes the combined dynamics of gravity and matter as the natural operating language of the screen:

$$S_{\text{eff}} = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \lambda R^2 + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi + \frac{1}{4g^2} F^2 + \dots \right]$$

and then interpret each term as the leading cost of maintaining coherence of a particular register sector: area (gravity), orientation (spinorial payload) and phase (gauge coherence).

Einstein regime ($R \ll M_s^2$): In the low-curvature regime, higher-curvature terms are suppressed and the variational principle is dominated by the linear response of the area register. Stationarity of the coherency cost around the BW/KMS vacuum, together with the entanglement first law, yields Einstein’s equation as the leading equation of state for the geometry [22–24].

Dirac transport regime (frozen g): Treating the background geometry (router) as fixed isolates the task of defining the minimal protocol for transporting the screen’s payload while preserving coherence. In this regime, the screen contributes a structural constraint often missing from standard entanglement-gravity derivations: the boundary completion explicitly fixes the admissible payload type. The $\mathbb{Z}_2$ twist/orientation structure identified in Chapter 1 means the fundamental payload is spinorial rather than vectorial, so the minimal coherence-preserving local transport operator is first order, selecting Dirac transport. This is the same minimal update rule logic that appears in independent information-processing derivations of Dirac dynamics, but here it is tied to the screen’s edge data and to the same fixed cutoff M_s that controls the gravitational sector [48].

Saturation regime ($R \sim M_s^2$): As curvature approaches the bandwidth scale, the register cannot resolve sharper gradients: higher-derivative response must become important. The minimal closure is the activation of the first subleading stiffness mode, $\mathcal{L}_{\text{sat}} \sim R + \lambda R^2$, which drives the system into the plateau universality class [38,51]. In the screen language, this is simply the statement that a finite-bandwidth medium cannot sustain unbounded response.

These regimes are not separate theories stitched together. They are the same fixed container / router / clock evaluated in different limits of information density [5,14].

2.7. Relation to Existing Approaches

Deriving Einstein dynamics from entanglement/relative entropy is a well-developed idea: Jacobson’s Einstein equation of state and later holographic/relative-entropy variants show that, near an entanglement equilibrium state, the first law structure $\delta S = \delta \langle K \rangle$ forces Einstein-like linear response [22–24,43]. In those approaches, however, the matter sector is typically assumed: one starts with a local QFT and its stress tensor, and gravity is inferred from its entanglement properties.

Deriving Dirac-type transport from information principles also has precedents, but these are usually developed independently of entanglement-gravity and without a shared physical cutoff that simultaneously fixes gravity, gauge normalization and mass budgets [48].

The screen framework supplies a single connectivity structure that supports both derivations simultaneously:

Fixed state space: Edge completion turns the subregion into a well-defined subsystem with a boundary-completed algebra $\mathcal{A}$ (Axioms P1–P3) [4,6]. This removes the usual ambiguity about what is held fixed when varying geometry in an entanglement-based argument.

Physical regulator: The stretched-horizon cutoff ($\delta = L_s = M_s^{-1}$, $\varepsilon = 1$) makes the modular integrals and the EFT expansion physically anchored (Axioms P4–P5) [10–12].

Router–payload distinction: The screen fixes not only the container (diamond) but also the data type of the payload (orientation/twist sector). That is what lets minimal coherence-preserving transport become a sharp selection rule for Dirac/Yang–Mills rather than an external assumption.

Extensive vs. intensive scaling: Gravity is an extensive stiffness of many channels, while gauge couplings are intensive susceptibilities normalized by coherent summation. This prevents the common conceptual slip of letting a large N renormalize dimensionless couplings in the wrong way, while still letting N_{eff} renormalize M_P^2 .

The spectral representation can thus be read in two complementary ways. In the spectral action tradition (NCG), one postulates a trace functional of a Dirac operator and expands it [18–20,44]. In the screen interpretation, the same trace is an effective controlled bookkeeping device: it is the local EFT expansion of the coherency cost, with a physical cutoff M_s and a physically fixed state space. The framework manages to treat GR (from entanglement) and Dirac (from transport) as sibling outputs of the same inference engine.

In this unified view, the hardware scale M_s acts as a universal speed limit. It sets a ceiling on two things at once: how much the geometry can curve before it flattens out (creating inflation) and how much energy a single particle can carry (setting the mass scale). In other words, as we will show in the [Appendices](#), inflation and particle masses are just two different ways of seeing the same bandwidth limit in action.

3. Geometric Origin of Constants and Cosmological Dynamics

In the proposed framework, the fundamental parameters of nature (particle masses, coupling strengths, cosmological parameters) are not arbitrary numbers that must be fitted to data. Once the system is calibrated by our sole dimensional input, Newton’s constant G , these quantities appear as the necessary operating settings of the screen itself, specifically its resolution (M_s), storage capacity (N), saturation limits and topological accessibilities.

This chapter compares our theoretical predictions ([Appendix A](#) through [E](#)) against observational data in a Coherency Ledger. From just one dimensional quantity (G) and 7 screen-natural axiomatic premises, we recover 17 observational targets, spanning more than sixty orders of magnitude, from the Planck scale (M_P) down to the cosmic acceleration floor (a_Λ), mostly at percent-level precision.

3.1. Coherency Ledger

Prediction: The value derived solely from Screen constants ($M_s, N, \kappa, \dots$).

Classification [X, Y]: Entries carry $[X, Y]$, where X specifies the comparator class and Y specifies the audit class:

X (Comparator): M = Measured, I = Inferred (from CMB), S = SM/RGE estimate, B = Bound, H = Heuristic.

Y (Audit Status): P = Primary (Direct hardware output, included in efficiency score), D = Dependent (Algebraic consequence), E = Exploratory.

Table 1. Coherency Ledger.

Quantity	Prediction	Observation	Deviation
Chapter 1 (Conceptual Foundations)			
Matter density Ω_m [M,P]	$1/\pi \approx 0.318$	0.315 ± 0.007	0.9%
Appendix A: Primordial Saturation and Capacity			
Scalar amplitude A_s [M,P]	2.08×10^{-9}	2.10×10^{-9}	1.0%
Spectral tilt n_s [M,P]	0.9646	0.9649	0.03%
Tensor ratio r [B,P]	0.0038	< 0.036	Consistent
Spectral running α_{run} [M,P]	-6.3×10^{-4}	-0.005 ± 0.007	Consistent
Scalaron mass M_R [I,D]	3.02×10^{13} GeV	3.00×10^{13} GeV	0.7%
R^2 stiffness λ_{R^2} [I,D]	5.42×10^8	5.44×10^8	0.4%
Coherence duration $\mathcal{N}_*$ [I,P]	$18\pi \approx 56.55$	56.98	0.76%
Appendix B: Gauge Couplings as Entropic Stiffness			
Fine-structure cst. α_0^{-1} [M,P]	137.035999216	137.035999206(11)	< 1 ppb
UV EM coupling $\alpha_{\text{em}}^{-1}(M_s)$ [S,P]	113.1	115 ± 3	1.5%
UV Strong coupling $\alpha_s^{-1}(M_s)$ [S,P]	37.7	38 ± 2	1.0%
Coupling Ratio $\mathcal{R}$ [S,D]	3.00	3.03	$\sim 1.0\%$
Weak mixing $\sin^2 \theta_W$ [S,P]	0.375	0.375 ± 0.005	Consistent
Appendix C: Electroweak Saturation and Mass Generation			
Higgs mass m_H [M,P]	125.7 GeV	125.25 ± 0.17 GeV	0.36%
VEV v [M,P]	246.3 GeV	246.22 GeV	0.03%
Top mass m_t [M,P]	174.2 GeV	172.69 ± 0.30 GeV	0.87%
Higgs quartic λ_H [I,D]	0.130	0.129	0.8%
Appendix D: Lepton Mass Spectrum			
Proton mass m_p [M,P]	942 MeV	938 MeV	0.5%
Mass ratio m_p/m_e (μ) [M,P]	$6\pi^5 \approx 1836.12$	1836.15	10^{-5}
Electron mass m_e [M,D]	0.511009 MeV	0.510999 MeV	2×10^{-5}
Muon mass m_μ [M,P]	104.25 MeV	105.66 MeV	1.3%
Tau mass m_τ [M,P]	1.788 GeV	1.777 GeV	0.6%
Tau lifetime τ_τ [M,D]	2.82×10^{-13} s	2.90×10^{-13} s	3.0%
Appendix E: Late-Time Cosmological Phenomenology from Finite-Resolution Boundaries			
Structure growth S_8 [M,E]	0.740	0.759 ± 0.024	Consistent
Horizon accel a_{H_0} [H,E]	1.04×10^{-10} m/s ²	$\sim 1.2 \times 10^{-10}$	13%
Vacuum floor a_Λ [H,E]	0.86×10^{-10} m/s ²	$\sim 1.2 \times 10^{-10}$	28%

3.2. Derivation Summary and Insights

Primordial Sector: Amplitude as a Capacity Limit (Appendix A)

In Appendix A, we view inflation as the screen constitutive response to high curvature ($R \sim M_s^2$). Operationally, finite capacity implies a bounded response ($f'(R) \rightarrow \text{const}$), which forces a plateau potential. Inflation is predicted as a universality class of a saturating medium rather than a tuned potential. The amplitude (A_s) is essentially the readout noise of this finite system ($A_s \propto 1/N$), transforming it from a free parameter into a precise hardware diagnostic. We also denote the spectral running as $\alpha_{\text{run}} \equiv dn_s/d \ln k$ to distinguish it from the strong coupling constant.

Gauge Sector: Screen as a Thermal Crystal (Appendix B)

In Appendix B, we connect forces to geometry. The stretched-horizon prescription fixes the modular integration domain ($\varepsilon = 1$), making the appearance of $\cot(1/2)$ a physical consequence of finite bandwidth rather than a regularization convention. This micro-macro homology implies that topology and thermodynamics are not separate postulates. Equivalently, the screen cannot be an

uncorrelated pixel gas; it must act as an impedance-matching lattice whose coordination promotes local modular noise into stable global invariants.

Mass Sector: Tension vs. Stiffness (Appendix C)

In [Appendix C](#), we derive particle masses by matching the screen's thermodynamic budget (E_{pix}) to its topological costs. The hierarchy mechanism is revealed here: M_p measures collective tension (many channels in parallel), while E_{pix} measures single-channel stiffness. Particle masses are saturation thresholds of a single channel, not suppressed Planck-scale mysteries.

Lepton Sector: Accessibility Modes (Appendix D)

In [Appendix D](#), we treat generations as accessibility modes. The electron, muon, and tau represent deeper dives into the screen geometry (Volume, Tangent, Fiber). Generation becomes a statement about which subalgebra of the boundary register a state has time to explore under the finite modular clock budget before it decoheres. The precise prediction of the mass ratio $\mu = m_p/m_e = 6\pi^5$ confirms the volume scaling of the manifold to high precision (10^{-5}).

Dark Sector: Gravity as Transmission Efficiency (Appendix E)

In [Appendix E](#), we explore a phenomenological extension where Dark Sector phenomena are modeled as the degradation of the screen's stiffness over time. Gravity is a transmissive medium; as the universe cools, the screen coherence fades ($f(z) < 1$). The framework is environment-selective: deep potential wells remain saturated (local $f \simeq 1$), while the shallow cosmological background experiences thermodynamic coherence loss. This shields the solar system while resolving large-scale tensions.

4. Conclusions and Outlook

This paper proposes a finite-resolution Coherency Screen as the minimal boundary ontology needed to define local physics in a diffeomorphism-invariant quantum theory. We work in a Wheeler–DeWitt setting ($\hat{H}\Psi = 0$) where the global state is constrained rather than time-evolved. In such a framework, the central operational problem is not to “quantize the graviton”, but to make a local subsystem well-defined when gravitational Hilbert spaces do not factorize cleanly across subregions.

Our proposal is that locality is organized by causal diamonds whose boundaries carry the minimal edge structure required for a consistent local algebra. Finite bandwidth then forces finite boundary capacity, and finite capacity implies a finite stiffness budget. In this view, gravity is the macroscopic response of a finite-capacity register.

4.1. Action as Distinguishability

Instead of postulating a fundamental geometric action for $g_{\mu\nu}$, we define diamond-local dynamics by an informational variational principle. For each causal diamond O , the reduced physical state ρ_O on the screen is treated as fixed data, while the geometric reference family $\sigma_O[g]$ is varied. The local coherency cost is:

$$S_{\text{coh}}[g; O] = S_{\text{rel}}(\rho_O \| \sigma_O[g]) \geq 0$$

Relative entropy functions here as an action because it measures, operationally, the mismatch between boundary correlations and their geometric description. In the small-diamond regime where modular flow is geometric (local KMS/Bisognano–Wichmann limit), stationarity of this cost yields Einstein-like linear response at leading order, and a controlled derivative/spectral expansion organizes higher-order corrections in standard EFT form.

This fixes a standard ambiguity: the screen hardware defines the constant data, while the geometry is simply the variable description.

4.2. Discretizing Capacity, Not Coordinates

The fundamental discretization in this framework is not a lattice of spacetime points. It is a count of independent coherency channels carried by the regulated boundary degrees of freedom. In the spirit of Heisenberg on the archipelago of Helgoland, we discretize boundary capacity, not coordinates, rendering the gravitational variational principle well defined.

The key master equation is the topology-locked channel multiplicity (screen depth):

$$N = \sqrt{2} \exp\left(8\pi + \frac{1}{6\pi}\right) \approx 1.226 \times 10^{11}$$

Concretely, N is the effective number of independent coherency channels (parallel strands) available per screen pixel to store and transmit the boundary edge data that keeps the vacuum geometry stable.

Here the Gauss–Bonnet baseline on the diamond S^2 cut supplies the bulk term, the tip completion supplies the finite-resolution defect term, and the minimal fermionic completion supplies the $\mathbb{Z}_2$ twist factor. This quantity N is not adjusted sector by sector but fixed upstream by the screen budget.

The constitutive relation connects the macroscopic stiffness M_P to the microscopic bandwidth M_s via the channel count:

$$M_P^2 = N_{\text{eff}} M_s^2 = (\kappa N) M_s^2$$

This fixes the fundamental resolution scale of the screen to:

$$M_s = \frac{M_P}{\sqrt{\kappa N}} \approx 3.02 \times 10^{13} \text{ GeV}$$

This result encodes a clear interpretation: M_s is the single-channel bandwidth (physical resolution), while M_P is the collective stiffness enhanced by parallelization across N_{eff} channels. Gravity is extensive in channel depth; gauge response is intensive and does not scale with N .

4.3. Cross-Sector Locking and Model Rigidity

Once Newton’s constant G fixes the overall stiffness scale, the remaining outputs are determined by discrete screen structure and regulator choices. [Chapter 3](#) summarizes this as a Coherency Ledger: 17 primary targets spanning inflationary statistics, gauge couplings, particle masses, and (as an explicitly exploratory extension) late-time phenomenology, with comparator classes stated explicitly (measured / inferred / SM-RGE / bound / heuristic). The notable feature is not any single agreement, but the way disparate sectors become correlated.

A useful way to express this rigidity is to adopt coherency units by setting $M_s = 1$. In these units, the structure is fixed by discrete screen data and the variational protocol; conventional units are recovered by the single conversion set by G . This is a highly non-trivial reduction of parametric freedom: a broad set of observables becomes a consistency web rather than independent inputs.

What the screen framework achieves, and what remains difficult for conventional bottom-up constructions, is the simultaneous locking of disparate sectors. It anchors the primordial inflationary scale directly to the screen capacity while fixing gauge force strengths through integer geometric counts. Furthermore, it replaces arbitrary mass parameters with rigid energy thresholds derived from a single pixel budget and organizes particle generations simply by the geometric depth accessible within a finite modular clock. This coupling of scales through a single finite-resolution boundary ontology is our central constructive claim.

The framework is built from seven screen-natural axioms that formalize what is needed for local physics in constrained gravity: Non-factorization, Operational Locality (Causal Diamonds), Edge Completion, Modularity (KMS), Finite Capacity, Gauge Topology (quantized edge structure), and Discrete Isotropy (minimal transport). In the screen context these are not ad hoc additions; they are the

minimal operational requirements to define subsystems, clocks, and regulated observables without assuming background structure.

4.4. Theoretical Lineage

This work stands on major developments by others. Entanglement-thermodynamic routes to gravity, edge-mode and subregion-algebra technology, and Chern–Simons/WZW boundary logic provide essential foundations. The spectral language and operator viewpoint of Noncommutative Geometry supply a natural scaffold for organizing the effective action and its matter/gauge sectors. Ideas associated with exceptional lattices (including E_8) are used here as stability and coding-efficiency guides for internal register structure under modular noise, not as a unification claim. In that sense, this paper aims to contribute a final connective layer: a fixed-hardware variational protocol that turns these ingredients into a single operational framework with correlated outputs.

4.5. Falsifiability and Outlook

The framework earns its rigidity by accepting strict, structural failure modes across all epochs. Because the primordial, gauge, and mass sectors are tightly coupled, the framework offers limited freedom for sector-by-sector tuning. Precision data can definitively rule it out through violations of the inflationary plateau relations, the breakdown of integer gauge locking, or deviations from the derived mass hierarchies; a failure in any single sector falsifies the entire construction.

We close with a final reflection for the reader: In this framework, the perceived reality is the most efficient geometric description of boundary correlations. It is not an extra structure added to quantum mechanics; it is the reference description that minimizes the coherency cost under the screen's fixed state space and bandwidth. The resulting form of macroscopic physics is therefore not a matter of arbitrary tuning, but a consequence of what a finite-capacity, boundary-completed quantum theory can represent consistently. In this sense, the observed universe emerges as the coherent expression of a unified operational information architecture.

Appendix A. Primordial Saturation and Capacity

This appendix derives the targets for the primordial sector (A_s, n_s, r) directly from the hardware specification established in [Chapter 1](#). We derive the inflationary parameters physically rather than treating them as arbitrary tunings of a scalar potential. By treating the vacuum as a finite-bandwidth register with a specific spectral aperture (fixed by the scale M_s), we identify inflation not as a new field, but as the inevitable saturation regime of the geometry itself.

Because the screen has a finite capacity (Axiom P5), it cannot resolve details smaller than the pixel size M_s . As curvature increases, the system eventually runs out of available states. This saturation causes the physical response to flatten out, naturally reproducing the Starobinsky plateau behavior without needing to tune arbitrary potentials (Section A.1).

As per Axiom P4, the vacuum behaves as a thermal state with an intrinsic modular clock [\[8,9\]](#). This allows us to define the duration of inflation physically: it is simply the time it takes for the screen coherence to decay due to information leakage (Section A.2). Finally, Section A.3 calculates the Primordial Amplitude (A_s) and Tilt (n_s) as direct statistical readouts of the screen capacity ($1/N$).

Appendix A.1. Geometric Stiffness and Activation

At low curvature, the screen reproduces General Relativity ([Chapter 2](#)). However, finite bandwidth (P5) places a hard limit on the EFT [\[15,46\]](#), as the registers cannot resolve gradients sharper than the pixel size M_s [\[10–12\]](#). As curvature approaches this limit ($R \rightarrow M_s^2$), the system runs out of distinguishable states and its response saturates. This saturation forces the effective potential to flatten, naturally locking the dynamics into the Plateau Universality Class (Starobinsky shape [\[38,51\]](#)). We have:

$$S_{\text{eff}} \approx \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R + \lambda_{R^2} R^2 \right]$$

To fix the stiffness coefficient λ_{R^2} , we relate the breakdown of the Einstein approximation to the hardware cutoff. In standard EFT, this term introduces a mass scale M_R defined by $\lambda_{R^2} = M_P^2 / (12M_R^2)$ [51]. If $M_R \ll M_s$, the theory suppresses modes the screen should resolve; if $M_R \gg M_s$, it implies a new physical hierarchy unrelated to hardware.

We identify the onset of stiffness with the spectral aperture limit M_s up to an order-unity factor ξ :

$$M_R \equiv \xi M_s, \quad \xi \sim \mathcal{O}(1)$$

We adopt the minimal no-hierarchy assumption $\xi = 1$:

$$M_R = M_s \simeq 3.02 \times 10^{13} \text{ GeV}$$

(Observed: $3.00 \times 10^{13} \text{ GeV}$ (inferred) [52]; Relative Deviation: 0.67%)

These observed comparator values are not direct measurements; they are values inferred within the same plateau dictionary from CMB observables. They are included only as a consistency translation check.

Substituting the hardware constitutive relation $M_P^2 = \kappa N M_s^2$ (from Ch. 1.5) into the definition yields a stiffness determined purely by topology:

$$\lambda_{R^2} = \frac{\kappa N M_s^2}{12(\xi M_s)^2} = \frac{\kappa N}{12\xi^2}$$

For $\xi = 1$, with $N \approx 1.226 \times 10^{11}$ and $\kappa = 1/6\pi$:

$$\lambda_{R^2} \simeq \frac{1}{12} \left(\frac{1}{6\pi} \right) (1.226 \times 10^{11}) \approx 5.42 \times 10^8$$

(Observed: 5.44×10^8 (inferred) [52]; Relative Deviation: 0.37%)

This large dimensionless number is not a tuned parameter; it is the direct manifestation of the channel multiplicity N .

Appendix A.2. Coherence Duration ($\mathcal{N}_*$)

We determine the duration of the inflationary phase by analyzing the stability of the screen coherent state against leakage.

In this framework, the relevant unit of evolution is the causal diamond (P2), and its boundary update is naturally counted in modular cycles (P4). In the high-curvature saturation regime (P5), every horizon-sized diamond operates near capacity. Consequently, the dimensionless digitization mismatch $\kappa = 1/6\pi$ derived from the discrete router geometry (P7) acts not as a localized defect, but as the characteristic impedance of the screen's transport network—a universal leakage parameter per diamond per modular cycle.

Coherence C is a resource depleted by this irreducible update cost. Assuming the effective loss rate is equipartitioned across the spatial transport axes ($D = 3$) due to isotropy (P7), the leakage probability per modular cycle is:

$$p \approx \frac{\kappa}{D} = \frac{1}{18\pi} \approx 0.0177 \ll 1$$

If the leakage probability per cycle is p , then after m modular cycles the remaining coherence is $C_m \simeq (1 - p)^m \approx e^{-pm}$, justifying the exponential decay approximation [8,9].

We define the Coherent Phase as the duration over which the accumulated entropic cost is less than the operational distinguishability threshold of 1 nat (i.e., when the reference model becomes statistically distinguishable from the boundary state) [40]:

$$\Delta S_{\text{leak}} \approx \int p d\tau_{\text{mod}} \approx \frac{\kappa}{D} \int d\tau_{\text{mod}} \sim 1$$

To convert this to the macroscopic e-fold clock $\mathcal{N}$, we assume the geometric matching $\eta \equiv d\mathcal{N}/d\tau_{\text{mod}} \approx 1$ and a threshold coefficient $c_{\text{exit}} \approx 1$.

$$\mathcal{N}_* = \frac{D}{\kappa} \left(\frac{c_{\text{exit}}}{\eta} \right)$$

Adopting the minimal stability values $c_{\text{exit}} = 1, \eta = 1$ and $D = 3$:

$$\mathcal{N}_* = \frac{D}{\kappa} = 3 \times (6\pi) = 18\pi \approx 56.55$$

(Observed: 56.98 (Inferred from n_s) [52]; Relative Deviation: 0.76%)

Appendix A.3. Primordial Observables

We now derive the observable targets. A key insight of the screen ontology is that the primordial amplitude is a capacity diagnostic: the boundary has N parallel channels, so by the Central Limit Theorem, the variance of the coarse-grained curvature readout must scale as $1/N$. The universe is smooth because the screen is deep.

Using the standard plateau dictionary [38,51] for the action derived in A.1, evaluated at the exit time derived in A.2, we obtain:

Scalar Amplitude (A_s)

The amplitude scales as $A_s \propto \mathcal{N}_*^2 / \lambda_{R^2}$. Using our derived forms $\lambda_{R^2} = \kappa N / (12\xi^2)$ and $\mathcal{N}_* \approx D/\kappa$, this yields the capacity form:

$$A_s = \frac{\mathcal{N}_*^2}{4\pi N} = \frac{(D/\kappa)^2}{4\pi N}$$

The factor 4π arises from integrating isotropic mode power over the standard S^2 angular measure. Substituting $D = 3$ and $\kappa = 1/6\pi$:

$$A_s = \frac{D^2}{4\pi\kappa^2 N} = \frac{9}{4\pi(1/36\pi^2)N} = \frac{81\pi}{N}$$

$$A_s \approx \frac{254.47}{1.226 \times 10^{11}} \simeq 2.08 \times 10^{-9}$$

(Observed: $2.10 \pm 0.03 \times 10^{-9}$ [52]; Relative Deviation: 0.95%)

Shape Parameters (n_s, r, α_s) follow the standard large- $\mathcal{N}$ plateau universality relations [51,53]:

$$n_s \approx 1 - \frac{2}{\mathcal{N}_*} = 1 - \frac{1}{9\pi} \approx 0.9646$$

(Observed: 0.9649 ± 0.0042 [52]; Relative Deviation: 0.031%)

$$r \approx \frac{12}{\mathcal{N}_*^2} = \frac{12}{(18\pi)^2} \approx 0.0038$$

(Observed: $r < 0.036$ [54]; Relative Deviation: Consistent)

$$\alpha_s \approx -\frac{2}{\mathcal{N}_*^2} \approx -6.3 \times 10^{-4}$$

(Observed: -0.005 ± 0.007 [52]; Relative Deviation: Consistent)

Consistency check: $\alpha_s = -r/6$.

Appendix A.4. Summary

We have shown that the primordial parameters of the universe are not arbitrary tunings but fixed capacity limits of the boundary. By treating spacetime as a finite-bandwidth information channel (Coherency Screen), we unify the high-energy inflationary phase with the low-energy gravitational description under a single operational definition: curvature is saturation.

This derivation involves no tunable parameters beyond G , except for two order-unity closure conventions ($\xi, c_{\text{exit}}/\eta$). We regard these parameters as admissible only within an order-unity window (e.g., $1/2 \dots 2$); outside this range, the closure would imply a new internal hierarchy. When we view the vacuum as a digital system with a physical limit M_s (rather than infinite field), the specific numbers of the early universe stop looking as random accidents. Instead, they emerge as natural result of the screen finite capacity (N).

What distinguishes this framework is the cross-link between hardware and dynamics. The same channel count (N) that fixes the low-energy Planck scale (Chapter 1) also determines the primordial amplitude via the Central Limit Theorem ($1/N$). The novelty lies in the identification of the inflationary clock not as a rolling scalar field, but as the decoherence time of the screen against modular leakage ($p \approx \kappa/D$). The striking result is that the large dimensionless numbers of cosmology ($N \sim 10^{11}$, $A_s \sim 10^{-9}$) are not random, but are locked to the discrete pixel count and geometric impedance, keeping standard effective potentials strictly in the role of phenomenological descriptions.

Appendix A.5. Model Compression Audit

Inputs: Screen hardware ($N \approx 1.2 \times 10^{11}$, $\kappa \approx 1/6\pi$, M_s) (Chapter 1); saturation scale M_s ; Standard Model/CMB data used only as external comparators.

Bridge: We identify inflaton potential with saturation of the boundary spectral aperture (finite bandwidth) [10,12].

Internal Mechanism: Microscopically, modular leakage ($p \sim \kappa/D$) sets the coherence clock $\mathcal{N}_*$; macroscopically, the Starobinsky plateau locks the trajectory to universality [38].

Sensitivity: Derived quantities scale with hardware/closure parameters as $\lambda_{R^2} \propto \kappa N \xi^{-2}$ and $\mathcal{N}_* \propto D \kappa^{-1} (c_{\text{exit}}/\eta)$; these propagate to observables as $A_s \propto N^{-1} D^2 \kappa^{-2} (c_{\text{exit}}/\eta)^2$, $r \propto \kappa^2 D^{-2} (\eta/c_{\text{exit}})^2$, and $1 - n_s \propto \frac{\kappa}{D} (\frac{\eta}{c_{\text{exit}}})$.

Outputs: Primordial amplitude $A_s \approx 2.08 \times 10^{-9}$ (saturation target); spectral tilt $n_s \approx 0.9646$; tensor-to-scalar ratio $r \approx 0.0038$; spectral running $\alpha_{\text{run}} \approx -6.3 \times 10^{-4}$; scalaron mass $M_R \approx 3.02 \times 10^{13}$ GeV; R^2 stiffness $\lambda_{R^2} \approx 5.42 \times 10^8$; coherence duration $\mathcal{N}_* \approx 56.55$ e-folds.

Falsifier: Hierarchy Violation: if data requires ξ significantly different from 1 (e.g., $M_R \ll M_s$), the activation closure is falsified; Plateau Violation: if future measurements find $r \ll 10^{-3}$ or violate the consistency relation $\alpha_s = -r/6$, the minimal $f(R)$ sector assumption is falsified; Tilt Shift: if n_s deviates significantly from 0.965, it implies the stability ratio $c_{\text{exit}}/\eta \neq 1$, forcing the introduction of a nuisance parameter.

Appendix B. Gauge Couplings as Entropic Stiffness

This appendix establishes the consistency of Standard Model gauge couplings with the coherency screen framework.

We derive the interaction strengths physically rather than treating them as arbitrary numbers. By treating the vacuum as a screen with a specific resistance to information flow (fixed by the scale M_s), we translate the abstract geometry of Noncommutative Theory [18,19] and E_8 lattices [17] into concrete,

observable forces. The framework acts as the requisite bridge, converting these abstract geometric symmetries into observable stiffness without introducing adjustable coupling constants.

Because the vacuum functions as a statistical state (P4), its response to charge fluctuation is rigorously defined by the Fisher Information metric [33]. Therefore, the gauge coupling is not a free parameter but a derived measure of modular stiffness—the vacuum’s resistance to information deformation. Gauge invariance of the edge algebra (P6) inherently quantizes this stiffness by the integer channel count (k). Consequently, the macroscopic normalization (4π) arises not as a separate postulate, but as the necessary coherent limit of the underlying modular noise, revealing thermodynamics and topology as dual descriptions of the same information capacity.

Section B.2 yields high-precision predictions for the Strong Sector based on intrinsic algebra invariants; Section B.3 establishes the Electromagnetic Prediction at the UV scale M_s , locking it to the electroweak intersection; and Section B.4 culminates with a stunning prediction for the Electromagnetic Sector at the IR limit (fine-structure constant).

Appendix B.1. Stiffness Quantization and Lattice Duality

We first establish the theoretical link between the screen discrete bits and continuous gauge fields. We define the inverse coupling α^{-1} as the stiffness of the vacuum—its resistance to gauge deformation. Formally, this is the Fisher Information metric, measuring the linear response (susceptibility χ_{tot}) to a charge perturbation λ [24]:

$$\alpha^{-1}(\mu) \equiv \chi_{\text{tot}}(\mu) = \left. \frac{d^2}{d\lambda^2} S_{\text{rel}}(\rho_\lambda \| \rho_0) \right|_{\lambda=0}$$

Gauge invariance of the Chern-Simons/WZW edge algebra (P6) forces the level $k \in \mathbb{Z}$, so stiffness is quantized by an integer edge count.

To compute this stiffness, we treat the vacuum as a Micro-Engine driven by Modular Noise: a KMS thermal state with respect to the Modular Hamiltonian (P4). To model the universal edge current algebra compatible with a topological boundary sector and integer quantization (P6), we use the standard Chern-Simons $\rightarrow$ WZW correspondence [49]. In linear response, the stiffness is the modular-circle integral of the connected charge correlator. Regulating the integral to the physical domain $[1, 2\pi - 1]$ (P5) yields the fundamental pixel susceptibility:

$$I_{\text{mod}} \equiv \int_1^{2\pi-1} \frac{d\tau}{\sin^2(\tau/2)} = 4 \cot(1/2) \implies \chi_{\text{pixel}} = k \cot(1/2)$$

The macroscopic normalization is fixed by flux on the operational S^2 cut of the diamond: the unit-flux normalization on a sphere introduces the geometric factor 4π (total solid angle) (Chapter 1, P2). However, the local pixel noise scales as $\cot(1/2) \approx 1.83$. This duality imposes a Macro-Rectification constraint: consistency requires a coherent normalization factor Ω_{coh} mapping the per-pixel modular susceptibility to the macroscopic flux convention. We fix Ω_{coh} via the constraint:

$$\Omega_{\text{coh}} \cdot \cot(1/2) \equiv 4\pi \implies \Omega_{\text{coh}} = \frac{4\pi}{\cot(1/2)} \approx 6.86$$

Impedance: the vacuum possesses internal geometric impedance; forces do not propagate freely but navigate a lattice that dictates summation rules.

Emergence: the sphere S^2 is not a background but an emergent coherent state, arising only because modular pixel noise sums coherently. This constraint justifies using the macroscopic form as the effective master formula:

$$\alpha^{-1}(M_s) = 4\pi \cdot k$$

Appendix B.2. Strong Sector Prediction

We now apply the stiffness relation $\alpha^{-1}(M_s) = 4\pi k$ to the non-abelian strong interaction ($SU(3)_c$). Unlike the Abelian electromagnetic sector where stiffness arises from matter screening ($\sum Q^2$), the non-Abelian stiffness is dominated by the gauge field self-interaction (antiscreening).

By P6 (Gauge Invariance), the boundary current algebra must form a representation of the bulk gauge group. For a non-Abelian sector, the edge stiffness is controlled by the algebra's intrinsic self-interaction invariant, namely the Dual Coxeter Number ($h^\vee$), which sets the natural normalization scale of the current algebra [55]. We therefore identify the minimal edge stiffness level with this invariant, $k_{\text{strong}} = h^\vee$.

For $SU(3)_c$, the dual Coxeter number is $h^\vee = N = 3$. Substituting this into the master formula:

$$\alpha_s^{-1}(M_s) = 4\pi \times 3 \simeq 37.7$$

(SM-inferred at M_s : $\alpha_s^{-1} \simeq 38 \pm 2$ [56,57] + running; Relative Difference: $\sim 1\%$)

This confirms that the strong coupling at unification is simply the geometric capacity of the $SU(3)$ fiber ($4\pi \times 3$). The factor of 3 difference between the strong ($k = 3$) and electromagnetic ($k = 9$) stiffness is responsible for the hierarchy of forces.

Appendix B.3. Electromagnetic Prediction at UV (M_s) and RGE Consistency Check

We now apply the same stiffness relation $\alpha^{-1}(M_s) = 4\pi k$ to the electromagnetic sector at the scale M_s . We posit that the screen couples to all long-range (hair) charges active in the vacuum.

Operationally, k_{em} is the total boundary current susceptibility: independent charged sectors contribute additively to the stiffness, so k_{em} is the sum of their squared charges (with color multiplicity). The fermions consist of 3 generations of quarks and leptons. For quarks (u, d) with $N_c = 3$ colors and charges $(2/3, -1/3)$, the sum is $3 \times [(2/3)^2 + (-1/3)^2] = 5/3$. Leptons (ν, e) contribute a charge sum of 1. This yields a total of $8/3$ per generation, or 8 for all three generations. The electroweak Higgs phase supplies one charged complex boundary current channel ($Q = 1$), contributing 1.

Substituting the integer sum $k_{\text{em}} = 8 + 1 = 9$ into the master formula:

$$\alpha_{\text{em}}^{-1}(M_s) = 4\pi \times 9 = 36\pi \simeq 113.1$$

(SM-inferred at M_s : $\alpha_{\text{em}}^{-1} \sim 115 \pm 3$ [56] + running; Relative Difference: $\sim 1.6\%$)

As an external consistency check, we now compare the prediction against Standard Model values extrapolated to the screen scale $M_s \simeq 3.02 \times 10^{13}$ GeV using standard 1-loop RGE coefficients $b_i = (41/10, -19/6, -7)$ [57]. The inverse couplings converge in the 10^{13} – 10^{14} GeV band. Specifically at M_s , α_1^{-1} and α_2^{-1} meet at approximately 42.6 and 42.4 respectively (an illustrative split of $\sim 0.5\%$). This crossing implies a weak mixing angle $\sin^2 \theta_W \approx 3/8 = 0.375$ at the screen, matching the canonical group-theoretic embedding. Checking the consistency with the unbroken basis using the relation $\alpha_{\text{em}}^{-1} = \alpha_2^{-1} + \frac{5}{3}\alpha_1^{-1}$:

$$42.4 + \frac{5}{3}(42.6) \approx 42.4 + 71.0 = 113.4$$

(Inferred at M_s from 1-loop SM running: 113.4; Relative Difference: 0.26%)

This is consistent with M_s lying in the electroweak intersection band, and it confirms that the predicted $\alpha_{\text{em}}^{-1}(M_s) = 4\pi k$ matches the SM unbroken-basis relation when $k = 9$.

Internal Consistency Check: Integer Locking of UV Couplings

Because both electromagnetic and strong couplings are defined by the same macroscopic flux normalization, their ratio is independent of any geometric or normalization convention. At the screen

scale M_s , the framework therefore predicts a purely integer relation. With $k_{\text{em}} = 9$ (three fermion generations plus the Higgs channel) and $k_{\text{strong}} = 3$ (the $SU(3)$ color fiber), this yields:

$$\frac{\alpha_{\text{em}}^{-1}(M_s)}{\alpha_s^{-1}(M_s)} = \frac{k_{\text{em}}}{k_{\text{strong}}} = \frac{9}{3} = 3$$

(SM-inferred at $M_s: \approx 3.03$; Relative Error $\sim 1\%$)

This integer locking is a direct consequence of boundary channel counting. Any additional light charged sector or modification of the gauge content would shift k and destroy the relation, making this a sharp falsifier of the framework.

Appendix B.4. Electromagnetic Sector at IR - Fine-Structure Constant (Geometric)

We now present an independent derivation targeting the low-energy fine-structure constant $\alpha(0)$ (Thomson limit). In this framework, the inverse coupling $\alpha^{-1}(0)$ represents the static ($\omega \rightarrow 0$) Kubo-Mori / Fisher susceptibility of the boundary state [7,33,40].

In the static limit, the Kubo-Mori metric reduces to an integral over the modular history of the uniform mode, so each independent accessible sector contributes in proportion to its invariant measure (invariant spectral weight) [46,47]. In the static limit, the susceptibility reduces to a trace over accessible modes; in spectral geometry, these trace coefficients are determined strictly by the invariant measures of the manifold (P4, Modularity).

Geometric resummation: Our derivation does not ignore quantum effects. We define $\alpha^{-1}(0)$ as a static Kubo-Mori susceptibility [7] of the fully interacting boundary state (renormalized low-frequency coefficient). Microscopic fluctuations and standard loop corrections are therefore already absorbed into this coarse-grained susceptibility, much as hydrodynamics packages microscopic collisions into constitutive laws. In the $\omega \rightarrow 0$ limit, the response reduces to a trace over accessible modes, which spectral geometry expresses through invariant measures. The geometric terms can thus be read as the resummed quantum response of the vacuum.

Because static susceptibilities are additive (susceptibilities add; sector capacities sum), the total response is the sum of the geometric capacities of all sectors accessible to the field.

We calculate α^{-1} by summing the independent geometric sectors enforced by Axioms P2 (Operational Locality, Reciprocity), P4 (Modularity) and P7 (Discretization).

Under P2, the measurement domain is a closed query-response loop. This requires a compact spatial closure; the minimal isotropic simply connected 3D closure is S^3 (rules out T^3 which introduces preferred cycles). Combined with the modular clock S^1 of period 2π (P4), the minimal covering domain is the product geometry $S^3 \times S^1$ [5,8,9].

However, the screen is an active register that resolves orientation. By P7 (Discretization), the router uses signed ports ($\pm$), implying a $\mathbb{Z}_2$ orientation label is operationally resolvable. This acts as a polarizing beam splitter, creating a second independent superselection channel (orientation bit adds an independent channel) [4,6]. We represent this channel by the quotient measures of the base geometry (orientation acts on both spatial loop closure and modular circle, so both quotients contribute).

Covering Sector ($S^3 \times S^1$): $\text{Vol}(S^3 \times S^1) = (2\pi^2)(2\pi) = 4\pi^3$

Parity Sectors (Additional $\mathbb{Z}_2$ Channels): $\text{Vol}(S^3/\mathbb{Z}_2) + \text{Len}(S^1/\mathbb{Z}_2) = \pi^2 + \pi$. By P7, the router resolves orientation ($\pm$). This $\mathbb{Z}_2$ bit acts independently on the spatial closure (S^3 by P2) and the modular clock (S^1 by P4). Since static susceptibilities are additive, these two independent parity channels contribute as a sum of their quotient measures.

As established in Chapter 1, the boundary capacity is fixed by the Euler class on the bifurcation S^2 , yielding $\text{Cap}(S^2) = \oint_{S^2} R^{(2)} dA = 8\pi$ (Chapter 1) [25,26].

By P5, the boundary acts as an Impedance Matcher between the continuous bulk and the discrete register. The mismatch reduces the effective susceptibility (mismatch lowers response). The unique

symmetric, dimensionless penalty constructible from bulk volume ($4\pi^3$) and boundary capacity (8π) without introducing an external scale is the inverse product (unique scale-free penalty) [10–12]:

$$\delta_{\text{imp}} \equiv -\frac{1}{\text{Vol}_{\text{bulk}} \cdot \text{Cap}_{\text{boundary}}} = -\frac{1}{(4\pi^3)(8\pi)} = -\frac{1}{32\pi^4}$$

By P7, the discrete octahedral router has $N_v = 6$ curvature-localizing vertices. Unlike flat faces, these corners act as diffractive defects that increase the system addressability [28].

Isotropy implies each vertex contributes equally; normalizing by the coordination $z = 6$ yields a prefactor of $N_v/z = 1$ (six corners, shared ports). The six vertices provide six independent phase addresses per cycle; in a scale-free normalization each contributes one factor of $(2\pi)^{-1}$, hence $(2\pi)^{-6}$ (six independent phase slots):

$$\delta_{\text{def}} \equiv +\left(\frac{N_v}{z}\right) \cdot \frac{1}{(2\pi)^6} = +\frac{1}{64\pi^6}$$

Summing these additive susceptibility contributions yields the inverse fine-structure constant:

$$\alpha^{-1} = \underbrace{4\pi^3}_{\text{Cover}} + \underbrace{\pi^2 + \pi}_{\text{Parity}} - \underbrace{\frac{1}{32\pi^4}}_{\text{Impedance}} + \underbrace{\frac{1}{64\pi^6}}_{\text{Defect}} \approx 137.035\,999\,216$$

(Observed: 137.035 999 206(11) [58]; Deviation: 1.0×10^{-8} ; $< 1\sigma$)

The first two terms represent the Leading-Order (LO) geometric capacity; the impedance and defect terms are the minimal Next-to-Leading Order (NLO) corrections required by finite bandwidth.

This derivation relies exclusively on the topology of the sphere ($4\pi, \pi$) and the octahedron ($8\pi, N_v = 6$). Changing the minimal structural choices destroys the match; for instance, dropping the $\mathbb{Z}_2$ orientation term removes $\pi^2 + \pi \approx 13.0$, destroying the precision agreement immediately.

Silent Band: The exponents ($\pi^3, \pi^2, \pi^1, \pi^{-4}, \pi^{-6}$) reflect the hardware architecture: π^{-4} term arises from the impedance penalty, defined as the inverse bulk–boundary product $(\text{Vol}_{S^3 \times S^1} \cdot \text{Cap}_{S^2})^{-1} \propto \pi^{-(3+1)}$ (P5), while the defect term scales as π^{-6} , reflecting the six equivalent phase slots of the router ($z = 6$) (P7). The silent band (absence of $\pi^{-1}, \pi^{-2}, \pi^{-3}$) therefore acts as a strong selection rule. If intermediate sectors were present with order-unity coefficients (c_i), they would shift $\alpha^{-1}(0)$ at the $\mathcal{O}(10^{-1})$ level (since $\pi^{-1} \approx 0.32, \pi^{-2} \approx 0.10$). Matching ppb precision would then require extreme fine-tuning ($|c_i| \lesssim 3 \times 10^{-8}$). In this sense, the static coupling has a code-like stability: within this minimal sector inventory it admits no mesoscopic contributions, responding primarily to global topology with only deeply suppressed corrections ($\delta_{\text{UV}}/\alpha^{-1} \approx 2 \times 10^{-6}$). This implies that the vacuum is remarkably clean, the silent band protecting the laws of physics from mid-scale noise.

The powers of two (32, 64) are not tuned coefficients but the unavoidable bit-depth of the register discrete bookkeeping. In this view, the small correction terms (π^{-4}, π^{-6}) are the signature of the boundary; they quantify the interface resistance and corner defect that survive coarse-graining.

Falsifiability: The two most precise measurements of α [58,59] disagree by $> 5\sigma$. Our axiomatic approach discriminates between them:

- **LKB 2020 (Rb)** [58]: 137.035 999 206(11) $\rightarrow$ Agreement
- **Berkeley 2018 (Cs)** [59]: 137.035 999 046(27) $\rightarrow$ Rejection

Our approach supports the LKB 2020 result (which notably also resolves the electron $g - 2$ tension in favor of the Standard Model).

Just as hydrodynamics replaces microscopic collisions with effective constitutive laws, the screen replaces the perturbative series of quantum loops with an Effective Action controlled by boundary topology. Geometric quantities therefore represent the resummed response of microscopic fluctuations, not their absence [15,60].

Appendix B.5. Summary

We have shown that the strengths of the fundamental forces are not arbitrary parameters but fixed thermodynamic properties of the boundary. By treating spacetime as a finite-bandwidth information channel (Coherency Screen), we unify the Ultraviolet (UV) and Infrared (IR) descriptions of gauge couplings under a single operational definition: Coupling is Stiffness. Edge completion fixes the boundary state space and the stretched-horizon cutoff fixes the modular integration domain, rendering the stiffness a defined observable rather than a convention-dependent normalization.

The screen functions as a coherent impedance-matching lattice rather than an uncorrelated pixel gas. Local modular fluctuations must sum coherently to match the global flux normalization, rigidly locking the UV couplings to discrete topological integers. The striking result is that the same screen geometry that locks UV couplings ($k = 9, 3$) also determines the IR fine-structure constant through static volumetric capacity. This construction is strictly falsifiable: the discovery of new light charged matter would disrupt these integer counts, breaking the precise agreement between the derived screen parameters and standard precision determinations.

Appendix B.6. Model Compression Audit

Inputs: Screen hardware scale $M_s \simeq 3 \times 10^{13}$ GeV and stretched-horizon regulator ($\delta = M_s^{-1}, \varepsilon = 1$) fixed upstream by [Chapter 1](#) [9]; edge-algebra quantization ($k \in \mathbb{Z}$) and macroscopic flux normalization (4π convention via P2). Standard Model RGEs are used only as external comparators.

Bridge: We identify the inverse coupling α^{-1} with the Fisher-Information (Kubo–Mori) susceptibility of the boundary state χ_{tot} to a charge deformation [7,33,40].

Internal Mechanism: Microscopically, the regulated modular-circle integral fixes a universal pixel-level susceptibility $\chi_{\text{pix}} = k \cot(1/2)$ [8]; macroscopically, screen coherence rectifies this into the flux-normalized master form $\alpha^{-1}(M_s) = 4\pi k$ [49].

Outputs: $\alpha_{\text{em}}^{-1}(M_s) \approx 113.1$ ($k_{\text{em}} = 9$); $\alpha_s^{-1}(M_s) \approx 37.7$ ($k_s = 3$); integer-locking relation $\alpha_{\text{em}}^{-1}/\alpha_s^{-1} = 3$; weak-mixing target $\sin^2 \theta_W(M_s) = 3/8 \approx 0.375$ (electroweak intersection); IR target $\alpha_0^{-1} \approx 137.036$ from geometric capacity.

Falsifier: Discovery of new light charged matter would alter k_{em} , breaking the UV locking; robust confirmation of Berkeley Cs result over LKB Rb would falsify IR geometric prediction [58,59].

Appendix C. Electroweak Saturation and Mass Generation

This appendix derives the mass scales of the electroweak sector (m_H, v, m_t) directly from the hardware specification established in [Chapter 1](#) ($M_s, N, d_\sigma = \sqrt{2}, \varepsilon = 1$). We introduce no continuous fit parameters; the mapping relies solely on these fixed constants and a set of minimalist operational closures required to map continuous fields onto a discrete register.

Appendix C.1. Unitary Pixel Budget (E_{pix})

We first establish the energy scale of a single pixel. In [Chapter 1](#), we derived the channel multiplicity $N = \sqrt{2} \exp(S_{\text{vac}})$ (P5). This count includes the Fermionic Completion factor ($d_\sigma = \sqrt{2}$), which provides the necessary spin-structure boundary conditions (twist sector) but does not offer an addressable payload channel for bulk excitations. We therefore isolate the payload depth $n_{\text{ch}} = N/\sqrt{2}$.

A screen-local elementary excitation corresponds to the coherent addressing of a payload code-word within the deep-pixel codebook. Since the codebook depth is N , the single-pixel coherent activation scale is suppressed from the hardware cutoff by the same entropic barrier (P5).

We define the unitary pixel budget E_{pix} as:

$$E_{\text{pix}} \equiv M_s e^{-S_{\text{vac}}} = \frac{\sqrt{2} M_s}{N} \approx 348.4 \text{ GeV}$$

This sets the characteristic single-pixel coherent activation scale for screen-local elementary excitations; heavier objects require multi-pixel encoding. We adopt the minimal closure $c_E = 1$, where $E_{\text{pix}} = c_E \sqrt{2} M_s / N$.

Appendix C.2. Higgs Boson: Entropic Saturation

The Higgs field serves as the metric of the internal charge space. Structurally, the Standard Model Higgs is a complex $SU(2)$ doublet containing 4 real scalar degrees of freedom $(\phi_1, \dots, \phi_4)$.

We determine the mass m_H as the thermodynamic cost of maintaining this structure against modular noise (P4, P5). In a KMS-thermal environment with finite resolution, the minimal cost to distinguish the state of an independent register slot at saturation is one bit ($\Delta I = \ln 2$). Since the Higgs register has 4 independent slots, the total minimal description length is $\Delta I_H = 4 \ln 2 = \ln 16$ nats.

Following the relative-entropy principle, m_H functions as an energy-per-nat stiffness for sustaining the Higgs register distinguishability against modular noise. Saturation occurs when $E_{\text{pix}} \approx m_H \cdot \Delta I_H$:

$$m_H = \frac{E_{\text{pix}}}{4 \ln 2} \approx 125.7 \text{ GeV}$$

(Observed: $125.25 \pm 0.17 \text{ GeV}$ [56]; Relative Difference: 0.36%)

Appendix C.3. Vacuum Expectation Value: Noise Floor Saturation

The Vacuum Expectation Value (v) corresponds to the coherent amplitude of the Higgs field in the vacuum. After gauge-fixing (removing 3 Goldstone modes), one radial order parameter remains.

We treat this mode as a signal in a bounded channel with peak capacity E_{pix} ; However, the screen cannot resolve the instantaneous modular phase (P4, P5).

Our ignorance of the phase implies a uniform prior over $[0, 2\pi)$. The physical observable v is the Root Mean Square (RMS) projection of the saturation amplitude E_{pix} :

$$v = \sqrt{\langle (E_{\text{pix}} \cos \phi)^2 \rangle} = \frac{E_{\text{pix}}}{\sqrt{2}} \approx 246.3 \text{ GeV}$$

(Observed: 246.22 GeV [56]; Relative Difference: 0.03%)

Appendix C.4. Top Quark: Dipole Coherence Limit

Fermions cannot exist as isolated local excitations due to gauge constraints (P6). The minimal screen-local fermionic excitation is a neutral dressed dipole ($f\bar{f}$) across the cut (Gauge-Invariant Dressing) (P3, P6). Its energetic cost scales as $E_{\text{dipole}} \simeq 2m_f c_{\text{dress}}$, where $c_{\text{dress}} \sim \mathcal{O}(1)$ accounts for minimal field energy.

Single-pixel coherence requires $E_{\text{dipole}} \leq E_{\text{pix}}$. If the dipole energy exceeds E_{pix} , the excitation cannot be represented within the single-pixel subalgebra and decays rapidly (P5). The top quark saturates this bound in the minimal closure $c_{\text{dress}} = 1$, giving:

$$m_t = \frac{1}{2} E_{\text{pix}} \approx 174.2 \text{ GeV}$$

(Observed: $172.69 \pm 0.30 \text{ GeV}$ [56]; Relative Difference: 0.87%)

The comparison is subject to intrinsic $\mathcal{O}(1 \text{ GeV})$ ambiguity between Monte Carlo and Pole mass definitions.

Appendix C.5. Structural Ratio Locks (Tree-level)

Because m_H , v , and m_t are derived from the same budget E_{pix} , their ratios are pure dimensionless numbers determined solely by the operational closures (P5).

Using the pole-mass identity $y_t^{\text{pole}} \equiv \sqrt{2} m_t^{\text{pole}} / v$, the model predicts the Top-Yukawa Coupling:

$$y_t^{\text{pole}} = \frac{\sqrt{2}(E_{\text{pix}}/2)}{E_{\text{pix}}/\sqrt{2}} = 1$$

In pole-mass variables, the identity $y_t \equiv \sqrt{2}m_t/v$ places the coupling near unity; translating to $\overline{\text{MS}}$ at $\mu = m_t$ yields a smaller value due to radiative corrections.

In the Standard Model Higgs Quartic Coupling λ is determined by the ratio of mass to VEV. Our derivation predicts:

$$\lambda = \frac{m_H^2}{2v^2} = \frac{1}{16(\ln 2)^2} \approx 0.130$$

(Observed: $\lambda \simeq 0.129$ inferred from global fits; Relative Difference: 0.8%)

These ratios are fixed directly by the geometry of the screen. To compare them with real-world measurements, we must apply the standard quantum corrections used in field theory.

Our result for the Higgs coupling ($\lambda \approx 0.130$) places the vacuum right on the edge of stability. Although we calculated this value specifically at the high energy scale M_s , it is striking that standard particle physics equations predict λ should drop to this near-zero critical level around the same energy range (10^{11} – 10^{13} GeV). This serves as a consistency check: our high-energy predictions align well with the low-energy physics observed today.

Appendix C.6. Summary

We have shown that the masses of the electroweak sector are not arbitrary free parameters but fixed saturation limits of the boundary register (P5). By defining the unitary pixel budget E_{pix} as the coherent activation scale of the screen (suppressed from the hardware cutoff M_s by the channel depth N), we unified the gravitational scale ($M_P^2 \sim \kappa N M_s^2$) with the particle scale ($m \sim \sqrt{2}M_s/N$).

We replaced the mechanical drag of the Higgs mechanism with the thermodynamic cost of maintaining bits against modular noise (P4, P5). The Higgs mass then emerges as the entropy limit ($4 \ln 2$), the VEV as the noise floor limit ($\sqrt{2}$) and the Top mass as the coherence limit ($1/2$).

When viewed as a digital signaling system, the masses are locked to integer ratios of the channel capacity. The vacuum does not select these masses; it simply clips any excitation that attempts to exceed the bit-depth of the screen.

Appendix C.7. Model Compression Audit

Inputs: Hardware scale $M_s \simeq 3 \times 10^{13}$ GeV and channel depth N (from [Chapter 1](#)); Twist factor $d_\sigma = \sqrt{2}$; Regulator $\varepsilon = 1$.

Bridges: Mass $\leftrightarrow$ Entropic/Coherence saturation on a finite-bandwidth register. Gravity: $M_P^2 = (\kappa N)M_s^2$; Particles: $E_{\text{pix}} = \sqrt{2}M_s/N$.

Closures: Entropic Activation E_{pix} activation; Binary Distinguishability $4 \ln 2$; Max-Entropy Phase $\sqrt{2}$; Dipole Coherence $1/2$, $c_{\text{dress}} = 1$.

Internal Mechanism: The channel depth N sets the entropic barrier between hardware cutoff and particle activation; thermodynamic rules (Landauer cost, variance, dipole dressing limit) dictate how this budget is partitioned among scalar entropy, noise floor, and spinor coherence.

Sensitivity: The Top-Yukawa lock $y_t = 1$ is sensitive to the $\mathcal{O}(1)$ dressing factor; vacuum stability consistency is sensitive to top-mass scheme inputs.

Outputs: Unitary budget $E_{\text{pix}} \approx 348.4$ GeV; Higgs mass $m_H \approx 125.7$ GeV; VEV $v \approx 246.3$ GeV; Top mass $m_t \approx 174.2$ GeV; Higgs quartic coupling $\lambda_H \approx 0.130$.

Falsifier: Definitive violation of $y_t^{\text{pole}} \approx 1$ (beyond dressing uncertainty); measurement of λ incompatible with 0.130; discovery of new light sectors that alter the edge bookkeeping N .

Appendix D. Lepton Mass Spectrum

This appendix derives the lepton family structure and mass spectrum (m_e, m_μ, m_τ) directly from the hardware specification established in [Chapter 1](#) ($M_s, \varepsilon = 1$) and the vacuum manifold $\mathcal{M}_{\text{pix}} \cong S^3 \times S^5$.

First, we explicitly derive the proton mass (m_p) from the screen scale (M_s) to demonstrate that the stable vacuum anchor is naturally generated by the hardware, not an arbitrary input. Then, having established the physical origin of this anchor, we use the precise empirical value of the proton mass to generate the lepton predictions.

This allows us to test the rigid geometric ratios of the screen topology to high precision (10^{-5}), isolating the geometric signal from the approximation errors inherent in the strong-force derivation.

Appendix D.1. Hadronic Anchor (m_p): Geometric Transmutation

While the screen hardware is fixed at M_s , the proton arises as a stable soliton at the infrared geometric transmutation scale. We explicitly derive this scale to show that the anchor is not arbitrary but generated by the hardware.

We derive the confinement scale Λ_{QCD} by running the strong coupling from the screen (M_s) down to the pole, driven by the geometric coupling $\alpha_s^{-1}(M_s) = 12\pi$ (Appendix B). We approximate the descent using a threshold-averaged 1-loop beta function with coefficient $\langle b_0 \rangle \approx 7.25$ (Effective Running).

$$\Lambda_{\text{QCD}} \approx M_s \cdot \exp \left[-\frac{2\pi(12\pi)}{\langle b_0 \rangle} \right] \approx 200 \text{ MeV}$$

The proton forms as the ground-state resonance of a minimal confinement cavity ($R \sim \Lambda_{\text{QCD}}^{-1}$). For a half-wave mode, $m_p \simeq c_p(3\pi/2)\Lambda_{\text{QCD}}$. Adopting the minimal closure $c_p = 1$ (Minimal Confinement Cavity):

$$m_p^{\text{mech}} \approx \frac{3\pi}{2} \Lambda_{\text{QCD}} \approx 942 \text{ MeV}$$

(Observed: 938 MeV [56]; Relative Difference $\sim 0.5\%$).

Appendix D.2. Spectral Selection Principles

We derive the lepton spectrum using a Spectral Accessibility model based on the edge-completed algebra $\mathcal{A}$ (Axioms P1–P3).

In the screen ontology, a particle is characterized by the edge-completed algebra $\mathcal{A}$ it can operationally access before it decoheres: Axiom P4 (Modularity) supplies a canonical local modular flow, and Axiom P5 (Finite Capacity) imposes a finite resolution (finite number of resolvable modular steps). As a result, short-lived excitations cannot resolve global identifications of the vacuum manifold; they only sample progressively more local structure. For any compact internal symmetry space, this coarse-to-fine accessibility has a canonical three-level hierarchy: global manifold (G), local tangent generators (g) and commuting phases (Cartan torus T).

The mass of an excitation scales inversely with the accessible phase volume (Ω) of the algebra it can explore during its lifetime (Accessibility Law):

$$m = \frac{m_{\text{anchor}}}{\Omega}$$

We interpret the modular lifetime of the particle as an effective spectral diffusion time (Spectral–Lifetime Bridge). Long lifetimes allow diffusion into the global structure of the manifold (low eigenvalues), while short lifetimes probe only the high-frequency local or fiber structure. Accordingly, finite modular exploration separates accessibility into these three canonical limits, following $G \rightarrow g \rightarrow T$ (global manifold, local generators, commuting phases).

The accessible algebra is determined by the number of screen-resolvable modular cycles available before decay, $n_\tau \equiv t_{\text{life}}/t_{\text{res}}$. Here $t_{\text{res}} \sim M_s^{-1}$ is sector-dependent and set by the finite resolution limit (P5); we require only the coarse ordering.

Global Regime ($n_\tau \gg 1$): Invariant under Group (G). Probes the Full Manifold ($S^3 \times S^5$) (global identifications resolvable). Anchor: IR (m_p).

Tangent Regime ($n_\tau \sim 1$): Invariant under Adjoint ($\mathfrak{g}$). Probes Local Generators (only local curvature/generators resolvable). Anchor: IR (m_p).

Fiber Regime ($n_\tau < 1$): Invariant under Cartan (T). Probes Commuting Phases (SM Gauge Torus $T^4/|\Gamma|$) (holonomy barrier). Anchor: UV (E_{pix}) due to Holonomy Barrier.

Increasing lifetime strictly expands the accessible algebra: $\mathcal{A}_{\text{fiber}} \subset \mathcal{A}_{\text{tangent}} \subset \mathcal{A}_{\text{global}}$ (Monotonicity Lemma).

Corollary: Large n_τ allows resolution of global identifications (mixing with the hadronic vacuum); intermediate n_τ resolves only local curvature. Short n_τ (prompt decay) hits the Holonomy Barrier, preventing resolution of the vacuum manifold. Under this barrier, the excitation cannot resolve the global soliton structure of the IR anchor m_p and defaults to the UV pixel activation scale E_{pix} (Appendix C).

Appendix D.3. Lepton Cascade

This filtration creates three generations of charged leptons corresponding to the topological limits of the vacuum geometry.

Electron (e): Global Regime. Accessible Geometry: Invariant Volume ($S^3 \times S^5$). Mass Formula: m_p/Ω_e .

Muon (μ): Tangent Regime. Accessible Geometry: Generator Count ($3 \times \mathfrak{su}(2)$). Mass Formula: m_p/Ω_μ .

Tau (τ): Fiber Regime. Accessible Geometry: Minimal Phase Volume ($T^4/|\Gamma|$). Mass Formula: $E_{\text{pix}}/\Omega_\tau$.

In each regime, Ω is the same object (accessible spectral phase volume); it reduces to a simple proxy appropriate to that limit: invariant volume for G , generator count for $\mathfrak{g}$ and torus measure for T .

Generation 1: Electron (Global Volume)

The electron is stable and explores the full geometry. The accessibility Ω_e is the product of the invariant volumes of the base S^3 ($2\pi^2$) and fiber S^5 (π^3), summed isotropically over the 3 spatial dimensions (P7 isotropy). This yields a rigid dimensionless ratio prediction:

$$\Omega_e = 3 \times (2\pi^2)(\pi^3) = 6\pi^5 \approx 1836.12$$

Using the empirical proton mass ($m_p^{\text{PDG}} \approx 938.272$ MeV) as anchor, the model predicts a ratio lock:

$$m_e = \frac{m_p^{\text{PDG}}}{6\pi^5} \approx 0.511009 \text{ MeV}$$

(Observed: 0.510999 MeV [56]; Relative Difference: $\sim 2 \times 10^{-5}$).

Generation 2: Muon (Local Tangent)

The muon decays before global mixing. The tangent regime probes the minimal isotropy sector $\mathfrak{su}(2)$ (P7, color is unresolved). With three spatial dimensions, the generator count is:

$$\Omega_\mu = 3 \times \dim(\mathfrak{su}(2)) = 9$$

$$m_\mu = \frac{m_p^{\text{PDG}}}{9} \approx 104.25 \text{ MeV}$$

(Observed: 105.66 MeV [56]; Relative Difference: 1.3%).

This tangent-level estimate uses a coarse generator-count proxy for Ω_μ ; without a refined local-accessibility graph, percent-level deviations are expected.

Generation 3: Tau (Minimal Fiber)

The Tau lifetime hits the Holonomy Barrier, switching to the UV anchor E_{pix} . Under the barrier, only the commuting gauge phases remain accessible (Minimal Commuting Phase). This corresponds to the Cartan torus of the Standard Model gauge group ($\text{rank} = 4$). We take the discrete quotient to be $|\Gamma| = 8$, the minimal identification inherited from the screen signed-port symmetry (P7, 2^3 independent sign bits). Using $E_{\text{pix}} \approx 348.4 \text{ GeV}$ (from Appendix C):

$$\Omega_\tau = \frac{(2\pi)^4}{8} = 2\pi^4 \approx 194.8$$

$$m_\tau = \frac{E_{\text{pix}}}{2\pi^4} \approx 1.788 \text{ GeV}$$

(Observed: 1.777 GeV [56]; Relative Difference: 0.6%).

Other discrete identifications would shift m_τ by an $\mathcal{O}(1)$ factor; we adopt here the minimal quotient mandated by P7.

Appendix D.4. Kinematic Consistency Check

We emphasize the distinction between static mass (capacity cost $1/\Omega$) and dynamic conductance (lifetime). The lifetime is governed by leakage through weak channels, scaling as $\Gamma \sim m^5/v^4$. We verify that the predicted mass m_τ yields a lifetime consistent with the regime switch. Using the standard EFT decay relation $\tau \propto m^{-5}$ and an order-unity channel closure $C_\tau \approx 5$:

$$t_\tau \approx t_\mu \left(\frac{m_\mu}{m_\tau} \right)^5 \frac{1}{C_\tau} \approx 2.82 \times 10^{-13} \text{ s}$$

(Observed: $2.9 \times 10^{-13} \text{ s}$ [56]).

Appendix D.5. Summary

We have shown that the lepton mass spectrum need not be treated as a random set of free parameters, but can be organized as a rigid cascade forced by the geometry of the vacuum. In the Screen framework, the vacuum is a finite-resolution register with a limited modular clock.

Indeed, Axioms P4 (modular flow) and P5 (finite resolution) turn the canonical Lie-theoretic filtration into a physical selector. This shift allows us to derive the three generations (e, μ, τ) as three canonical accessibility modes of the underlying manifold $S^3 \times S^5$.

Standard field theory assumes all particles see the same vacuum geometry; the Screen framework recognizes that short-lived excitations hit a Holonomy Barrier—they simply cannot explore global structure before they decay. This maps the three generations to the standard Lie-theoretic filtration of symmetry: the Electron samples the Global Group (G), the Muon resolves only local algebraic structure ($\mathfrak{g}$), and the Tau is confined to the commuting Cartan fiber (the torus of phases T). We treat mass, lifetime and accessibility as a self-consistent triplet.

The key mechanism is the Anchor Switch: the reference scale itself changes when global mixing is inaccessible. The Electron and Muon are light because they reference the hadronic vacuum scale (m_p); the Tau is heavy because its prompt decay forces it to couple directly to the screen UV pixel budget (E_{pix}).

Once the vacuum is treated as a finite Coherency Screen, the electron mass emerges as a precise geometric fraction of the proton ($m_p/6\pi^5$) and the three-generation structure follows from the minimal canonical accessibility limits of a Lie group.

Appendix D.6. Model Compression Audit

Inputs: Hardware constants M_s, E_{pix} ; Geometry $\mathcal{M}_{\text{pix}} \cong S^3 \times S^5$; Strong coupling $\alpha_s^{-1} = 12\pi$.

Bridge: Mass $\propto$ Anchor / Accessibility (Ω). Stable states couple to IR anchor (m_p); prompt states to UV anchor (E_{pix}).

Closures: Proton Running; Accessibility Law/Spectral Bridge; Modular Selector/Anchor Switch; Isotropy; Rank-4 Cartan/Minimal Quotient $|\Gamma| = 8$.

Internal Mechanism: The modular lifetime of the state selects the accessible submanifold of the vacuum geometry (Monotonicity Lemma). Long lifetimes allow global volume exploration (G); short lifetimes restrict the state to local (g) or fiber (T) structures.

Sensitivity: Proton mass sensitive to β -function thresholds; Tau mass sensitive to discrete quotient choice ($|\Gamma|$).

Outputs: Anchor Mode (Precision Test): Input $m_p^{\text{PDG}} \rightarrow$ Predicts m_e (2×10^{-5} precision), m_μ (1.3%); End-to-End Mode (Mechanism): Input $M_s, \alpha_s \rightarrow$ Predicts m_p (0.5%) $\rightarrow$ Implies m_e (0.5%), UV Sector: Input $E_{\text{pix}} \rightarrow$ Predicts m_τ (0.6%); lifetime τ_τ (3.0%).

Falsifier: Deviation of the geometric ratio m_p/m_e from $6\pi^5$; discovery of a 4th generation (geometry exhausted); failure of the Anchor Switch logic.

Appendix E. Late-Time Cosmological Phenomenology from Finite-Resolution Boundaries

This appendix derives the asymptotic cosmological behaviors of the vacuum (inflation and dark sector freezeout) from the hardware limits of the Coherency Screen.

[Appendix A](#) has already derived the primary inflation predictions (A_s, n_s, r). Here, we (i) restate the hardware reason inflation must be plateau-like and (ii) derive late-time deviations from a Λ CDM baseline (freezeout $f(z)$, S_8 suppression, horizon acceleration scale a_0). We do not attempt to derive the full Λ CDM expansion history $H(z)$ from first principles; we treat it as a comparator baseline and predict specific deviations imposed by the screen.

Inputs fixed upstream include M_s (P5), $\varepsilon = 1$ (P4–P5), $\kappa \approx 0.053$ ([Chapter 1](#), tip impedance), coordination $z_{\text{coord}} = 6$ (P7) and the horizon thermodynamics setting (P4).

Appendix E.1. UV Regime: Information Saturation

Standard inflation allows arbitrary potentials $V(\phi)$. However, a finite-resolution screen cannot support infinite curvature, as this would imply an infinite bit density, violating the bandwidth limit M_s . The gravitational response function $f(R)$ must thus saturate at high curvature to preserve the finite information density of the screen (Bounded Information Principle). In the Einstein frame, this saturation forces the effective scalar potential to flatten asymptotically as $V(\phi) \rightarrow \text{const}$, creating a geometric attractor that locks the physics into the Plateau Universality Class.

Consequently, the observable parameters depend primarily on the number of e-folds N_* , yielding a rigid conditional prediction. For the simplest saturation profile (Starobinsky $R + R^2$):

$$n_s \approx 1 - \frac{2}{N_*}, \quad r \approx \frac{12}{N_*^2}$$

Low tensors follow from plateau universality and the screen clock N_* (derived in [Appendix A](#)), interpreted as a finite number of coherent modular operations. Quantitative targets for n_s, r, A_s are detailed in [Appendix A](#); we do not repeat them here.

Appendix E.2. IR Regime: Thermodynamic Freezeout (S_8)

At late times, the horizon temperature drops and the screen ability to mediate long-range forces degrades. We model this as a running coherence efficiency $f(z) \in (0, 1]$, representing the fraction of long-range gravitational flux coherently transmitted by the horizon at epoch z .

We apply $f(z)$ to the growth sector (effective clustering strength $G_{\text{eff}} = f(z)G_N$) while using the standard Λ CDM $H(z)$ as a comparator expansion history.

Freezeout activates when the vacuum energy fraction $\Omega_\Lambda(z)$ dominates the screen intrinsic lattice binding threshold, set by the geometric coupling $\kappa \approx 0.053$ (Chapter 1). We define the onset redshift z_{fr} by the condition $\Omega_\Lambda(z_{\text{fr}}) \approx \kappa$.

We adopt $\Omega_\Lambda \sim \kappa$ as the minimal hardware threshold; other percolation thresholds would shift z_{fr} by order unity but introduce extra assumptions. Using Planck 2018 parameters, this defines a derived onset redshift of $z_{\text{fr}} \approx 2.39$.

Below this threshold, the efficiency decays. Under Axiom P7, the minimal isotropic coordination is $z_{\text{coord}} = 6$ (Coordination Equipartition). Maximum-entropy sharing of thermal noise across these ports suggests a cooling exponent $\nu = 1/z_{\text{coord}} = 1/6$.

$$f(z) = \begin{cases} 1 & z \geq z_{\text{fr}} \\ \left[\frac{H(z)}{H(z_{\text{fr}})} \right]^{1/6} & z < z_{\text{fr}} \end{cases}$$

This suppression applies only to the linear cosmological background. We postulate that $f \rightarrow 1$ whenever local acceleration $a \gg a_0$ (or in deep potential wells), ensuring that virialized systems like the Solar System remain saturated and satisfy local gravity constraints (Environmental Screening).

Prediction (S_8)

The suppression of growth leads to a lower S_8 parameter. For the present day ($z = 0$), we find $f(0) \approx 0.81$. Using the standard growth-index approximation ($S_8 \propto G_{\text{eff}}^{0.55}$):

$$S_8^{\text{pred}} \approx S_8^{\text{Planck}} \cdot f(0)^{0.55} \approx 0.832 \cdot (0.81)^{0.55} \approx 0.740$$

(Observed DES Y3: 0.759 ± 0.024 [61]; Planck Baseline: 0.832).

A full growth equation integration is the next step; the growth-index estimate is sufficient to show the scale of the effect. Different weak-lensing analyses (DES, KiDS, HSC) report slightly different values; we use DES Y3 [61] as a representative comparator.

The framework resolves the tension by predicting a value consistent with weak lensing, derived structurally from the lattice properties of the screen.

Appendix E.3. Acceleration Floor (a_0)

The screen has a minimum thermal noise floor determined by the horizon temperature $T_H = \hbar H / 2\pi k_B$.

We identify the acceleration scale a_0 (associated with MOND-like phenomenology) as the irreducible thermal Vacuum Noise Floor:

$$a_0 \sim a_{\text{min}} = \frac{cH_0}{2\pi} \approx 1.04 \times 10^{-10} \text{ m/s}^2$$

(Observed MOND scale: $\approx 1.2 \times 10^{-10} \text{ m/s}^2$ [62]).

We compare this to the asymptotic vacuum floor $a_\Lambda \approx 0.86 \times 10^{-10} \text{ m/s}^2$. The framework targets the scale 10^{-10} m/s^2 ; the remaining factor of ~ 1.4 is likely geometric/order-unity and not derived here. This suggests a_0 is a thermodynamic necessity of a universe with a causal horizon. The same screening rule naturally leaves high-acceleration regimes Newtonian while allowing modifications near $a \sim a_0$.

Appendix E.4. Summary

We have re-framed cosmology by treating the cosmic horizon as a physical, finite-resolution screen. This shifts the focus from inventing new invisible substances to solving a single hardware problem: what can a finite-bandwidth boundary actually transmit?

This approach is highly constrained because we do not introduce tunable parameters. The same constants defined in [Chapter 1](#) (M_s , lattice impedance κ and connectivity $z_{\text{coord}} = 6$) dictate the asymptotic behaviors.

In the early universe (UV), the screen saturates. Just as a sensor cannot record infinite signal, the screen cannot support infinite curvature. This capacity limit naturally forces inflation into a stable plateau (quantified in [Appendix A](#)), avoiding runaway singularities without fine-tuning.

In the late universe (IR), the screen freezes out. As the universe cools, the screen's ability to transmit gravity degrades, producing a controlled weakening of structure growth (an S_8 -scale suppression) and revealing a horizon-set thermal noise floor (a_0). If the tension currently seen across instruments persists, this mechanism offers a cleaner candidate for the signal, as it relies on the thermodynamic properties of the horizon rather than new particle interactions.

The major insight is that gravity is a transmissive phenomenon: the "Dark Sector" can be reinterpreted as predictable thermal behavior of the spacetime medium itself, saturating when hot and freezing out when cold. Because these effects are tied to specific hardware thresholds, the model is strictly falsifiable: if precision growth and lensing data show no coherence fading, this late-time extension is ruled out.

Appendix E.5. Model Compression Audit

Inputs: Hardware constants $M_s, \kappa \approx 0.053, z_{\text{coord}} = 6$; Baseline Cosmology (Planck 2018 parameters for $H(z)$ background comparator).

Bridge: Gravity $\leftrightarrow$ Transmissive Coherence. UV finite bandwidth $\rightarrow$ Plateau Inflation. IR thermodynamic cooling $\rightarrow$ Growth Suppression.

Closures: Information Saturation; Thermodynamic Decoupling trigger κ ; Coordination Equipartition $\nu = 1/6$; Vacuum Noise Floor.

Internal Mechanism: The screen acts as a variable-efficiency transmitter. It saturates at high energy (inflation) and freezes out at low energy (S_8), with transition points determined by hardware thresholds (M_s, κ).

Sensitivity: The S_8 prediction depends linearly on the cooling exponent ν ; a different lattice topology (e.g., $z_{\text{coord}} = 4$) would alter the result.

Outputs: UV: Conditional prediction $r \sim 1/N_*^2$ (Plateau Class); $z_{\text{fr}} \approx 2.39$; Structure growth $S_8 \approx 0.740$ (resolving tension); Horizon acceleration $a_{H_0} \approx 1.04 \times 10^{-10} \text{ m/s}^2$; Vacuum acceleration floor $a_\Lambda \approx 0.86 \times 10^{-10} \text{ m/s}^2$.

Falsifiers: Detection of primordial tensor modes with $r > 0.01$ (rules out plateau saturation); precise measurement of S_8 confirming the Planck value (rules out freeze-out); absence of MOND-like behavior at the horizon scale; or if growth suppression is required at $z \gg z_{\text{fr}}(\kappa)$.

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