Supplement: Foundations and Microscopic Origins of the Entropic Scalar EFT

Introduction: Purpose of this Appendix

The main text of Chinitz (2025) (1) introduces a compelling theoretical framework suggesting that many fundamental aspects of our physical universe—including gravity, the inertia of matter (mass), the flow of time, and even cosmological phenomena typically attributed to dark matter and dark energy—might all emerge from the underlying dynamics of quantum entanglement entropy. This entire program is efficiently captured within an Effective Field Theory (EFT). This EFT centers on a single dynamical scalar field, denoted $S_{\text{ent}}(x)$, which quantifies local deficits in vacuum entanglement entropy, and introduces a fundamental constant, κ_m, that establishes a direct relationship between mass and information (measured in bits).

Given the potentially profound implications of this framework, readers may naturally ask crucial questions about its foundations. This appendix aims to address these, providing a more detailed exploration of the Entropic Scalar EFT's theoretical underpinnings and its mathematical consistency, specifically targeting readers who may be encountering these ideas for the first time. We will address two main points:

Q1 Microscopic Origins: Where does the postulated S_{ent} field originate? Can it be connected to or derived from more established or candidate fundamental theories of quantum gravity, providing a microscopic basis for its existence and properties?

Q2 Mathematical Consistency: Is this EFT a mathematically sound theoretical structure? Can it be quantized using standard methods? Is it well-behaved under quantum corrections (renormalization)? Is it free from theoretical issues like unphysical "ghost" states or instabilities, especially in strong gravitational fields?

To answer these questions, this appendix is structured as follows:

- **Section 1:** We will first provide a detailed exposition of the Entropic Scalar EFT itself, carefully explaining its action, deriving its field equations, and elaborating on the physical meaning of its key components, including the mass-bit equivalence law and the concept of entropic time dilation.

- **Sections 2 & 3:** We will then explore how this EFT might naturally emerge from two distinct candidate quantum gravity frameworks. Section 2 discusses the entanglement-augmented Group Field Theory (GFT), based on the work of Liu et al. (2023) (2). Section 3 discusses the Information-Complete Quantum Field Theory (ICQFT) proposed by Chen (2023) (3). We will provide brief conceptual introductions to GFT and ICQFT and detail how the EFT's structure (S_{ent}, κ_m, dynamics) maps onto the constructs within these deeper theories.

- **Section 4:** We will present a detailed derivation investigating the intriguing possibility that gauge forces (like electromagnetism and the nuclear forces) could also emerge from this framework, arising from entropy deficits specific to different charge sectors, governed by the fundamental principle of gauge invariance.

- **Section 5:** We will discuss the mathematical health of the EFT, covering its quantization, behavior under quantum loop corrections (renormalization group flow), and results from stability checks.

- **Section 6:** Finally, we will synthesize these findings, summarizing the coherent, layered picture that emerges, connecting microscopic quantum information principles to observable macroscopic physics.

Our approach emphasizes pedagogical clarity, aiming to explain the physical intuition behind the mathematical formalism at each step.

A   The Entropic Scalar Effective Field Theory (EFT)

The foundational concept of this framework (1) is that the quantum vacuum is not truly empty but possesses a rich structure characterized by a maximum density of entanglement between quantum field fluctuations. When ordinary matter forms or aggregates, the constituents become entangled internally (e.g., quarks within a proton, electrons in an atom) or are constrained in ways that reduce their entanglement with the surrounding vacuum fluctuations. This displacement or "using up" of vacuum entanglement creates a local deficit relative to the maximally entangled vacuum state. This deficit is the central object of the EFT.

A.1   The Scalar Field $S_{\text{ent}}(x)$: Quantifying Missing Entanglement

The local entanglement entropy deficit is described by a real scalar field, $S_{\text{ent}}(x)$, defined throughout spacetime.

- **Physical Interpretation:** At any point x, the value of $S_{\text{ent}}(x)$ represents the amount of entanglement entropy (typically measured in bits) that is absent compared to what would be present in the pure, maximally entangled vacuum state at that location. A larger value of $S_{\text{ent}}(x)$ corresponds to a greater deficit (less entanglement present).

- **Expected Behavior:** In vast regions devoid of matter, such as cosmic voids, the vacuum is nearly pristine, so the entanglement deficit is minimal; we can normalize $S_{\text{ent}}(x) \to 0$ in this limit. Conversely, within or near concentrations of matter (where mass density $\rho(x)$ is high), significant vacuum entanglement is displaced, resulting in a larger deficit, $S_{\text{ent}}(x) > 0$.

A.2   The EFT Action and Field Dynamics

The interplay between this entanglement deficit, gravity, and matter is governed by an effective action principle. The proposed action combines the standard Einstein-Hilbert action for General Relativity ($I_{EH} = \int d^4x \sqrt{-g}\frac{c^4}{16\pi G}R$) with terms describing the S_{ent} field (1):

$$I[g, S_{\text{ent}}] = \int d^4x \, \sqrt{-g} \underbrace{\left[\underbrace{\frac{c^4}{16\pi G}R}_{\text{Gravity}} + \underbrace{\frac{\gamma}{2} g^{\mu\nu}\partial_\mu S_{\text{ent}} \, \partial_\nu S_{\text{ent}}}_{\text{Kinetic term for } S_{\text{ent}}} \underbrace{-\lambda S_{\text{ent}}}_{\text{Potential term}} \underbrace{-\kappa\rho S_{\text{ent}}}_{\text{Matter coupling}} \right]}_{\mathcal{L}} \quad (1)$$

Let's examine the components of the Lagrangian density $\mathcal{L}$:

- $\frac{c^4}{16\pi G}R$: This is the familiar term describing the dynamics of spacetime geometry (metric $g_{\mu\nu}$) via the Ricci scalar R. G is Newton's gravitational constant, and c is the speed of light.

- $\frac{\gamma}{2} g^{\mu\nu}\partial_\mu S_{\text{ent}} \, \partial_\nu S_{\text{ent}}$: This is the standard kinetic energy term for a scalar field S_{ent}. It involves gradients ($\partial_\mu S_{\text{ent}}$) contracted with the inverse metric ($g^{\mu\nu}$). The constant γ is dimensionless (often set to 1 by choice of units or normalization of S_{ent}) and acts as a "stiffness" parameter: a larger γ makes it energetically costly for the entanglement deficit field to change rapidly in space or time.

- $-\lambda S_{\text{ent}}$: This term represents a potential energy for the field, linear in S_{ent}. The constant λ could be interpreted as driving the field towards some equilibrium value or setting an overall energy offset for the vacuum state related to its baseline entanglement. Often, its

effects can be absorbed into boundary conditions or the definition of the vacuum state ($S_{\text{ent}} = 0$), so it might be effectively set to zero in many applications.

- $-\kappa \rho S_{\text{ent}}$: This crucial term describes the direct interaction between ordinary matter, represented by its mass density $\rho(x)$, and the entanglement deficit field $S_{\text{ent}}(x)$. The coupling constant κ determines the strength of this interaction, quantifying how effectively mass density acts as a source or sink for entanglement (specifically, as a source for the deficit S_{ent}).

The dynamics of the S_{ent} field are found by applying the Euler-Lagrange equation, $\frac{\delta I}{\delta S_{\text{ent}}} = 0$, to the action Eq. (1). This yields:

$$\gamma \nabla^2 S_{\text{ent}} = \lambda + \kappa \rho \tag{2}$$

Here, $\nabla^2 \equiv g^{\mu\nu} \nabla_\mu \nabla_\nu$ is the covariant d'Alembertian operator (the wave operator in curved spacetime). **Interpretation:** This field equation dictates how the entanglement deficit propagates and responds to matter. The $\kappa \rho$ term shows that matter density directly sources the deficit. The $\gamma \nabla^2 S_{\text{ent}}$ term acts like inertia or tension, resisting rapid changes and causing the deficit to spread or smooth out. If we choose our baseline vacuum state such that $\lambda = 0$, the equation simplifies to a form directly analogous to the Poisson equation of Newtonian gravity:

$$\boxed{\nabla^2 S_{\text{ent}} = \frac{\kappa}{\gamma} \rho} \tag{3}$$

Physical Meaning: This striking parallel ($\nabla^2 S_{\text{ent}} \propto \rho$ vs $\nabla^2 \Phi \propto \rho$) strongly suggests that the entanglement deficit field S_{ent} plays a role similar to that of the gravitational potential Φ. It implies that gravity itself might be interpreted, at least partly, as an emergent effect driven by gradients in the entanglement structure of spacetime, caused by the presence of matter. Where ρ is high, S_{ent} increases (more deficit), leading to spatial variations that could manifest as gravitational attraction.

A.3 Modified Gravity and the Entanglement Stress-Energy Tensor

The S_{ent} field doesn't just respond to matter; it also influences spacetime geometry. This is found by varying the action Eq. (1) with respect to the metric $g_{\mu\nu}$. The result is the standard form of Einstein's Field Equations, but with an additional source term on the right-hand side arising from the S_{ent} field:

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} \left(T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\text{ent})} \right)$$

Here, $T_{\mu\nu}^{(\text{matter})}$ is the stress-energy tensor of ordinary matter and fields, while $T_{\mu\nu}^{(\text{ent})}$ is the stress-energy tensor associated with the entanglement deficit field itself:

$$T_{\mu\nu}^{(\text{ent})} = \gamma \left(\partial_\mu S_{\text{ent}} \partial_\nu S_{\text{ent}} - \frac{1}{2} g_{\mu\nu} (\partial_\alpha S_{\text{ent}} \partial^\alpha S_{\text{ent}}) \right) + g_{\mu\nu} (\lambda S_{\text{ent}} + \kappa \rho S_{\text{ent}}) \tag{4}$$

Interpretation: This equation shows explicitly how the entanglement deficit contributes to the curvature of spacetime. The first term (in parentheses) is the standard stress-energy contribution from the kinetic energy of a scalar field – regions where S_{ent} is changing rapidly carry energy and momentum. The second term shows that the field's value itself (via λ and the coupling to ρ) contributes an energy density and pressure, similar to a cosmological constant or quintessence field. Through these contributions, gradients and concentrations of entanglement deficit S_{ent} source gravity, providing a mechanism by which these informational effects can mimic the gravitational influence typically attributed to dark matter (1). For example, a slowly varying S_{ent} field extending far beyond a galaxy's visible matter could generate the additional gravitational pull needed to explain flat rotation curves.

A.4 Mass-Bit Equivalence: Inertia from Information

Perhaps the most radical postulate of this framework is a proposed fundamental equivalence between inertial mass (m) and the information content (S_{ent}, measured in bits) associated with a particle or system (1):

$$\boxed{m = \kappa_m \, S_{\text{ent}}} \tag{5}$$

Interpretation: This law suggests that what we perceive as mass is not an intrinsic property but rather a manifestation of the entanglement deficit a particle imposes on or carries relative to the vacuum. A particle *has* mass *because* it corresponds to a certain amount of "missing" vacuum entanglement. The constant κ_m serves as a universal conversion factor: the mass associated with one bit of entanglement deficit. **Value and Origin:** The value $\kappa_m \approx 8.9 \times 10^{-31}$ kg/bit is obtained by calibrating Eq. (5) using the known mass of the electron, assuming it corresponds to $S_{\text{ent}} \approx 1$ bit. The Chinitz paper (1, Appendix X) further provides a theoretical derivation of this value starting from Planck scale physics. This involves arguments based on black hole thermodynamics (Bekenstein-Hawking entropy) and renormalization group (RG) flow, suggesting how the fundamental Planck-scale entanglement tension runs down to the observed low-energy value κ_m due to geometric dilution and statistical effects, potentially following a scaling law $S \propto (L_P/l)^{5/2}$. **Distinction from Γ_{gal}:** It is vital to distinguish this fundamental, microscopic constant κ_m from the *emergent*, macroscopic ratio $\Gamma_{gal} \approx 10^{-16}$ kg/bit discussed in (1) in the context of galactic dynamics. Γ_{gal} represents the average amount of *baryonic mass* in a galaxy associated with one bit of entanglement deficit in the *entire galactic halo*. It reflects collective effects and the inefficiency of ordinary matter in creating large-scale deficits, whereas κ_m is proposed as the fundamental mass-per-bit at the particle level.

A.5 Entropic Time Dilation: Time from Entanglement Flow

Just as S_{ent} influences spatial geometry, it also affects the progression of time (1). The proposed relationship connects the rate of local proper time ($d\tau$) to a global coordinate time (dt, e.g., cosmological time) via the local entanglement deficit:

$$\frac{d\tau}{dt} \approx \frac{S_{\text{ent}}(x)}{S_0} \tag{6}$$

Here, S_0 represents a reference state, potentially the maximum entropy state (minimum deficit $S_{\text{ent}} \approx 0$) found in deep cosmic voids. (Note: if S_{ent} measures entropy directly, the relation might be inverted, $d\tau/dt \propto S_0/S_{\text{ent}}$, such that higher entropy = faster clock). Assuming Eq. (6) with S_{ent} as deficit: **Interpretation:** Time flows more slowly (smaller $d\tau/dt$) in regions where the entanglement deficit S_{ent} is large (i.e., where entropy is low). Conversely, time flows at a reference rate ($d\tau/dt \approx 1$ if $S_{\text{ent}} \approx S_0$ represents the reference state, or faster if S_{ent} can exceed S_0 somehow, although deficit usually implies $S_{\text{ent}} \geq 0$) where entanglement is maximal. This concept is reportedly derivable within the full framework (1, Appendix A.1.1, A.2.3) and offers a mechanism to explain the observed apparent acceleration of cosmic expansion and the tension between different measurements of the Hubble constant (H_0) without invoking dark energy (1). Observers in low-entropy (high S_{ent} deficit) regions like our local galactic neighborhood would experience time running slower than observers in high-entropy (low S_{ent} deficit) void regions, leading to the perception of accelerated expansion when looking out.

B Emergence from Entanglement-Augmented GFT

Could the S_{ent} field and its associated physics arise naturally from a more fundamental theory of quantum gravity? Group Field Theory (GFT) provides one candidate framework.

GFT Conceptual Overview: GFT (2) envisions spacetime itself as emergent, not fundamental. The basic constituents are "quanta of geometry," perhaps analogous to Planck-scale "atoms of space." GFT uses the mathematical tools of quantum field theory to describe the interactions and collective behavior of these quanta. A smooth spacetime, like the one described by General Relativity, is expected to emerge in a specific phase of the GFT system, often described as a "condensate" where a vast number of quanta correlate in a coherent way. GFT aims for a background-independent formulation of quantum gravity.

Liu et al.'s Entanglement Scalar ϕ: Liu et al. (2) significantly extended the GFT framework by introducing an additional scalar field, ϕ, associated with the fundamental GFT quanta. This ϕ field has a dual role:

- It explicitly encodes the degree of quantum *entanglement* between different GFT quanta (representing different nascent parts of spacetime).

- It serves as an internal, *relational clock*. The evolution or "flow" of the GFT system, particularly its emergence towards a classical spacetime, can be described with respect to changes in ϕ.

Mapping GFT to the Entropic EFT: The structure developed by Liu et al. allows for a mapping to the phenomenological Entropic Scalar EFT:

- $S_{\text{ent}}(x)$ **and the GFT Entanglement Scalar ϕ:** The macroscopic EFT field $S_{\text{ent}}(x)$ quantifies the local *deficit* in entanglement entropy relative to the vacuum. In the GFT framework developed by Liu et al. (2), a scalar field ϕ is introduced which encodes the degree of microscopic entanglement[cite: 559]. Since a larger GFT scalar ϕ corresponds to *more* microscopic entanglement links, this implies a *smaller* macroscopic deficit S_{ent}. Therefore, the appropriate mapping reflecting their inverse relationship is $S_{\text{ent}} \propto 1/\phi^n$ for some $n > 0$. Choosing the specific mapping $S_{\text{ent}}(x) \propto 1/\phi^2(x)$ directly aligns the GFT lapse function $N \propto 1/\phi^2$ (derived by Liu et al. [cite: 963]) with the EFT's postulate $d\tau/dt = N \propto S_{\text{ent}}/S_0$ (Eq. (6)), resolving the apparent discrepancy discussed in the 'Dynamics' section below.

- $\gamma \leftrightarrow Z_\phi$: The "stiffness" γ of the S_{ent} field in the EFT's kinetic term reflects how easily the underlying GFT field ϕ can vary. This is determined by the wave-function renormalization constant Z_ϕ in the GFT dynamics. The relation $S_{\text{ent}} \approx \sqrt{Z_\phi}\phi$ leads to the kinetic term correspondence $\frac{\gamma}{2}(\partial S_{\text{ent}})^2 \leftrightarrow \frac{Z_\phi}{2}(\partial\phi)^2$ (requiring $\gamma = 1$ if Z_ϕ is absorbed in S_{ent}'s normalization).

- $\kappa_m \leftrightarrow \alpha$ **(GFT Mass Scale):** The GFT analysis reveals that the emergent Hamiltonian includes terms related to entanglement, effectively acting like a mass term $H_{\text{mass}} \propto \alpha\langle\phi^2\rangle$. The overall strength α was previously undetermined within GFT. This framework proposes identifying this scale α with the inverse of the fundamental mass-per-bit constant, $\alpha \propto 1/\kappa_m$. This crucial step uses the empirically grounded κ_m from the EFT to fix the emergent mass scale within the fundamental GFT, bridging the two theories.

- **Dynamics (Poisson Eq. & Lapse):** The GFT framework utilizes a Hamiltonian constraint, which, similar to General Relativity, relates spacetime curvature to energy/matter sources. In the continuum limit analysis reported by Liu et al. (2), this constraint reduces to the structure of the gravitational Hamiltonian (often formulated in Ashtekar variables). Within this structure, terms arising from the GFT entanglement scalar ϕ contribute to the effective source density. In the appropriate weak-field, static limit, the Hamiltonian constraint then naturally yields a Poisson-like equation where the emergent potential (related to metric components and thus to curvature) is sourced by these entanglement deficits. The emergence of the Poisson equation structure is thus consistent. Regarding the lapse

5

function N (where $d\tau = Ndt$), the analysis by Liu et al. (2), when mapping to the GR Hamiltonian structure, yields $N(r) = 1/(2K^{(2)}\varphi^2(r))$, where φ is the GFT field mode amplitude. A potential reconciliation with the EFT postulate $d\tau/dt = N \propto S_{\text{ent}}/S_0$ (Eq. (6)) arises if we adopt an *inverse* relationship between the EFT entanglement deficit field S_{ent} and the GFT scalar ϕ (assuming $\varphi \approx \phi$). Specifically, if larger ϕ represents *more* microscopic entanglement, and larger S_{ent} represents a larger *deficit* (less entanglement), then a natural mapping is $S_{\text{ent}} \propto 1/\phi^2$. With this identification, the GFT result $N \propto 1/\phi^2$ directly implies $N \propto S_{\text{ent}}$, bringing the GFT derivation into alignment with the EFT's entropic lapse function. This suggests the initial mapping $S_{\text{ent}} \propto \phi$ was likely incorrect, and the inverse-square relationship provides consistency.

GFT Contribution Summary: Entanglement-augmented GFT offers a potential microscopic foundation for the Entropic Scalar EFT. It provides a "bottom-up" picture where spacetime geometry, the S_{ent} field, its dynamics, its link to mass via κ_m, and even the flow of time emerge from the collective quantum behavior of entangled "atoms of space."

C Emergence from Information-Complete QFT (ICQFT)

An alternative, more "top-down" perspective comes from Information-Complete Quantum Field Theory (ICQFT), as proposed by Chen (3).

ICQFT Conceptual Overview: ICQFT posits that the universe is described by a single, holistic quantum state $|\Psi_{\text{univ}}\rangle$. This state encompasses degrees of freedom that we typically separate into matter, gauge fields, and gravity—in ICQFT, these are fundamentally inseparable aspects of one entangled system (a "trinary" system). Spacetime geometry, particle properties, and even the arrow of time are emergent features encoded within the intricate entanglement structure of this universal state. The theory aims to be background-independent and information-centric.

ICQFT Entropy Relation and Λ: A key result cited from ICQFT (3) concerns the entanglement entropy associated with a region of spacetime. It's found to generally contain two contributions: one proportional to the boundary area A (the holographic term) and another proportional to the bulk volume V:

$$S_{\text{tot}} = \frac{A}{4L_P^2} + \mu\,\frac{V}{L_P^3}$$

The coefficient μ of the volume term is a dimensionless universal constant reflecting the density of bulk entanglement in the vacuum state. Crucially, Chen argues that this volume entanglement term μ provides a natural explanation for the observed cosmological constant Λ. When deriving Einstein's equations from thermodynamic principles using this entropy relation, the μ term directly generates a cosmological constant term $\Lambda \propto \mu G/L_P^3$.

Mapping ICQFT to the Entropic EFT:

The ICQFT framework, while conceptually distinct, provides strong support for the structure of the Entropic Scalar EFT. Here's how the key elements map:

- $S_{\text{ent}}(x) \leftrightarrow$ **Local Volume Entropy Density:** The EFT's scalar field $S_{\text{ent}}(x)$, representing the local entanglement deficit, is identified with the density arising from the *volume entanglement term* $(\mu V/L_P^3)$ in the ICQFT entropy relation $S_{\text{tot}} = A/(4L_P^2) + \mu V/L_P^3$. In the maximally entangled vacuum state (e.g., deep cosmic voids), this volume entanglement density is maximal, corresponding to a baseline state (e.g., $S_{\text{ent}} \approx S_0 \sim \mu/L_P^3$). The presence of matter alters the local quantum state, reducing the achievable volume

entanglement and thus creating a deficit (a deviation of S_{ent} from this baseline S_0, or an increase in S_{ent} if defined as deficit $S_{\text{ent}} = S_0 - S_{\text{actual}}$).

- $\kappa_m \leftrightarrow \mu$ **(via Λ):** The connection between the mass-per-bit constant κ_m and the ICQFT volume entanglement constant μ arises through the cosmological constant Λ. Here's the conceptual link:

  1. In thermodynamic derivations of gravity (like Jacobson's approach cited in (1)), entropy relates to energy flow. A constant background entropy density, such as the μ/L_P^3 arising from volume entanglement in ICQFT, contributes a constant energy density ρ_{vac} and pressure p_{vac} to the effective stress-energy tensor of the vacuum.

  2. The nature of this volume entanglement (isotropically distributed) typically implies an equation of state $p_{\text{vac}} = -\rho_{\text{vac}}$. A stress-energy tensor with this property ($T_{\mu\nu}^{(\text{vac})} = -\rho_{\text{vac}} g_{\mu\nu}$) is mathematically identical to the cosmological constant term in Einstein's equations, where $\Lambda = 8\pi G \rho_{\text{vac}}/c^4$.

  3. Thus, ICQFT provides a potential microscopic origin for Λ: ρ_{vac} is identified with the energy density associated with the volume entanglement μ.

  4. The energy density associated with this volume entanglement must also be consistent with the fundamental mass-energy-per-bit scale set by κ_m. The energy density can be estimated as (energy per bit) $\times$ (bits per volume) $\approx (\kappa_m c^2) \times (\mu/L_P^3)$.

  5. Equating the two expressions for the vacuum energy density gives the consistency relation:
  $$\rho_\Lambda = \frac{\Lambda c^4}{8\pi G} \approx \frac{\mu(\kappa_m c^2)}{L_P^3}$$

  This provides a powerful theoretical link: the observed value of the cosmological constant Λ and the fundamental mass-information constant κ_m together determine the value of the ICQFT volume entanglement parameter μ. The extremely small observed Λ implies that $\mu \approx 10^{-123}$, interpreted as meaning the volume entanglement contribution is incredibly dilute on the Planck scale, consistent with the view that ordinary matter constitutes a very sparse informational perturbation within the universe.

- **Entropic Lapse & Dynamics:** ICQFT proposes that time is not fundamental but emerges from the evolution of the universe's entanglement structure, with the arrow of time defined by the direction of increasing entanglement.

  1. If the global progression of time dt tracks the overall increase in entanglement, then the rate at which local physical processes unfold (measured by local proper time $d\tau$) can plausibly depend on the local entanglement state.

  2. Regions with maximal entanglement (low deficit S_{ent}) might represent the "fastest" possible local clock, aligned with the global rate. Regions with significant entanglement deficits (high S_{ent}) are further from this maximal state and might have less capacity for rapid entanglement evolution, leading to a slower local clock.

  3. This provides a fundamental justification within ICQFT for the entropic lapse function relationship $d\tau/dt \propto S_{\text{ent}}/S_0$ (or similar, depending on precise definitions) postulated in the EFT.

  4. Furthermore, the entire universal quantum state $|\Psi_{\text{univ}}\rangle$ in ICQFT must satisfy overarching consistency conditions (related to information completeness or possibly extremizing some entanglement-related action). These global conditions necessarily constrain the allowed configurations and dynamics of any emergent, coarse-grained

fields like $S_{\text{ent}}(x)$. This constraint mechanism implicitly dictates the effective field equations that S_{ent} must obey, leading to dynamics consistent with the EFT equation (Eq. (2)).

ICQFT Contribution Summary: ICQFT provides a potentially unifying, information-first foundation where S_{ent} emerges as a measure of volume entanglement within the universe's single quantum state. This framework naturally connects S_{ent} dynamics to the cosmological constant Λ and the nature of time itself, lending strong conceptual support to the EFT.

D Gauge Forces from Entropic Deficits – Detailed Derivation

Beyond gravity, can other fundamental forces, like electromagnetism, also be understood within this entropic framework? This section details a derivation suggesting that gauge forces might emerge from deficits in entanglement specific to different types of conserved charges (like electric charge).

D.1 Charge-Specific Entanglement Deficit $S_Q(x)$

We begin by postulating that for each type of conserved charge (e.g., U(1) electric charge), there exists a corresponding scalar field $S_Q(x)$.

- **Interpretation:** $S_Q(x)$ measures the local deficit in entanglement specifically within the "channel" or sector associated with that charge Q. For instance, $S_{EM}(x)$ would measure the deficit in entanglement related to electromagnetic interactions.

- **Sourcing by Charge Density:** Just as mass density ρ sources the gravitational entropy deficit S_{ent}, the density of charge $\rho_Q(x)$ acts as a source for $S_Q(x)$. This leads to an analogous Poisson-like equation:

$$\nabla^2 S_Q(x) \;=\; \frac{\kappa_Q}{\gamma_Q}\, \rho_Q(x) \tag{7}$$

  where κ_Q is the coupling (bits deficit per unit charge) and γ_Q is the stiffness for this specific entropy field sector.

D.2 Local Baseline Invariance and the Gauge Principle

The core idea is that the absolute baseline value of $S_Q(x)$ is physically meaningless, similar to how the absolute phase of a quantum wavefunction or the absolute value of electric potential is unobservable. Only *differences* in S_Q between points should affect physics. Furthermore, the underlying quantum gravity theories (GFT/ICQFT) might possess inherent redundancies allowing local adjustments of the entanglement baseline without changing physical outcomes.

We therefore demand that the effective theory describing S_Q must be invariant under *local* shifts of this baseline:

$$S_Q(x) \;\longrightarrow\; S_Q'(x) = S_Q(x) + \Lambda(x) \tag{8}$$

where $\Lambda(x)$ is an arbitrary function of spacetime coordinates.

Now, consider the standard kinetic term for S_Q: $\mathcal{L}_0 = \frac{\gamma_Q}{2}(\partial_\mu S_Q)(\partial^\mu S_Q)$. Under the local shift Eq. (8), the derivative transforms as $\partial_\mu S_Q \to \partial_\mu S_Q' = \partial_\mu S_Q + \partial_\mu \Lambda$. Substituting this into $\mathcal{L}_0$ reveals terms involving $\partial_\mu \Lambda$, showing that $\mathcal{L}_0$ is *not* invariant under local shifts.

To restore invariance, we invoke the gauge principle: introduce a new field that compensates for the unwanted terms. We introduce a vector field $A_\mu(x)$ and require it to transform

simultaneously with S_Q in such a way that a new combination remains invariant. The required transformation for A_μ is precisely that of a U(1) gauge potential:

$$A_\mu(x) \longrightarrow A'_\mu(x) = A_\mu(x) + \partial_\mu \Lambda(x)$$

With this, we define the *gauge-covariant derivative*:

$$D_\mu S_Q \equiv \partial_\mu S_Q - A_\mu$$

Let's check its transformation property:

$$
\begin{aligned}
D'_\mu S'_Q &= \partial_\mu S'_Q - A'_\mu \\
&= (\partial_\mu S_Q + \partial_\mu \Lambda) - (A_\mu + \partial_\mu \Lambda) \\
&= \partial_\mu S_Q - A_\mu \\
&= D_\mu S_Q
\end{aligned}
$$

The covariant derivative $D_\mu S_Q$ is indeed invariant under the combined local transformations. Therefore, constructing the kinetic term using this derivative, $\mathcal{L}_{\text{kin}} = \frac{\gamma_Q}{2}(D_\mu S_Q)(D^\mu S_Q)$, guarantees invariance under the local entropy baseline shifts.

Physical Interpretation of A_μ: The vector field A_μ emerges as the necessary "connection" field required to compare the arbitrary entropy baselines at infinitesimally separated points x and $x + dx$. It essentially encodes the information about how the baseline shifts from point to point.

D.3 Field Strength, Action, and Maxwell's Equations

Once the connection field A_μ is introduced via the gauge principle, its natural curvature is the gauge-invariant field strength tensor:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \tag{9}$$

This is mathematically identical to the electromagnetic field strength tensor.

The most general, minimal, gauge-invariant Lagrangian describing the dynamics of S_Q, A_μ, and their coupling to a source current $j_Q^\mu = (\rho_Q, \mathbf{j}_Q)$ associated with the charge density ρ_Q is:

$$\mathcal{L} = -\frac{1}{4g^2} F_{\mu\nu} F^{\mu\nu} + \kappa_Q A_\mu j_Q^\mu + \frac{\gamma_Q}{2}(D_\mu S_Q)^2 \tag{10}$$

Here, g is the gauge coupling constant for this interaction. The first term is the standard Maxwell Lagrangian for the gauge field A_μ. The second term describes the interaction of the potential A_μ with the charge current j_Q^μ, with κ_Q determining the coupling strength (related to the charge sourcing S_Q). The third term is the gauge-invariant kinetic term for the entropy field S_Q.

Applying the Euler-Lagrange equation for A_ν to this Lagrangian yields the field equations for A_μ. The variation gives:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu A_\nu)} \right) - \frac{\partial \mathcal{L}}{\partial A_\nu} = 0$$

$$\partial_\mu \left(-\frac{1}{4g^2}(4F^{\mu\nu}) \right) - \left(\kappa_Q j_Q^\nu + \frac{\gamma_Q}{2}(2(D^\mu S_Q)\frac{\partial(D_\mu S_Q)}{\partial A_\nu}) \right) = 0$$

Using $\frac{\partial(D_\mu S_Q)}{\partial A_\nu} = -g_\mu^\nu$, the last term becomes $+\gamma_Q D^\nu S_Q$. This term might represent a current associated with the S_Q field itself or contribute to a mass term for A_μ (like the Proca term if

S_Q were constant, or related to the Higgs mechanism). If we focus on the equation sourced by the external current j_Q^ν, we have:

$$\partial_\mu \left(\frac{1}{g^2} F^{\mu\nu} \right) = \kappa_Q j_Q^\nu + [\text{terms involving } D^\nu S_Q]$$

Setting aside the $D^\nu S_Q$ term for now (assuming it vanishes in relevant limits or describes other physics), we recover Maxwell's inhomogeneous equations:

$$\partial_\mu F^{\mu\nu} = g^2 \kappa_Q j_Q^\nu \tag{11}$$

This demonstrates that the dynamics associated with the emergent connection A_μ sourced by the charge current j_Q^ν are precisely those of electromagnetism, provided the constants are matched appropriately (e.g., identifying $g^2 \kappa_Q$ with the standard electromagnetic coupling).

D.4 Non-Abelian Generalization

This entire construction can be generalized to non-Abelian gauge groups, such as SU(2) or SU(3), which describe the weak and strong nuclear forces.

- Promote the entropy deficit S_Q and the connection A_μ to be matrix-valued fields living in the Lie algebra of the group (e.g., $S_Q = S_Q^a T^a$, $A_\mu = A_\mu^a T^a$, where T^a are the group generators).

- Replace the simple difference in the covariant derivative with a commutator: $D_\mu S_Q = \partial_\mu S_Q - ig[A_\mu, S_Q]$.

- Replace the definition of the field strength with the non-Abelian version involving commutators: $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]$.

- Construct the gauge-invariant Yang-Mills action: $\mathcal{L}_{\text{YM}} = -\frac{1}{4}\text{Tr}(F_{\mu\nu}F^{\mu\nu}) + ...$ (including couplings to matter and the S_Q kinetic term).

This standard procedure yields the dynamics of non-Abelian gauge theories. The underlying principle remains the same: demanding local invariance for the baseline of sector-specific entropy fields S_Q^a forces the introduction of the corresponding non-Abelian gauge potentials A_μ^a.

Conclusion for Gauge Forces: This detailed derivation shows how the mathematical structure of U(1) (electromagnetism) and potentially non-Abelian (Yang-Mills) gauge theories can formally emerge from applying the gauge principle to scalar fields $S_Q(x)$ representing charge-specific entanglement deficits. The key physical input is the postulate that the absolute baseline of these entropy fields is unobservable and locally redundant, possibly rooted in the structure of underlying quantum gravity theories.

E Quantisation, Loops, and Stability

A viable physical theory must be quantizable and mathematically well-behaved. This section discusses checks on the quantum consistency and stability of the Entropic Scalar EFT.

E.1 Canonical Quantisation

On a fixed (e.g., flat) spacetime background $g_{\mu\nu}$, the S_{ent} field can be quantized using standard canonical procedures.

- The canonical momentum conjugate to S_{ent} is $\pi_S = \frac{\partial \mathcal{L}}{\partial(\partial_0 S_{\text{ent}})} = \gamma \dot{S}_{\text{ent}}$ (where $\dot{S}_{\text{ent}} = \partial_0 S_{\text{ent}}$).

- Imposing the equal-time commutation relation $[S_{\text{ent}}(t, \mathbf{x}), \pi_S(t, \mathbf{y})] = i\hbar\delta^{(3)}(\mathbf{x} - \mathbf{y})$ allows the construction of creation and annihilation operators and a corresponding Fock space.

- **Interpretation:** The "quanta" created by these operators are not new fundamental particles but represent collective excitations or propagating ripples in the entanglement deficit field of the vacuum.

E.2 One-Loop Renormalisation and RG Flow

When the EFT is coupled to other quantum fields (like Standard Model fermions), quantum loop corrections will modify the parameters $(\gamma, \lambda, \kappa, \kappa_m)$ of the original Lagrangian. Analyzing these corrections determines if the theory remains predictive (renormalizable).

- **Beta Functions:** One-loop calculations reportedly yield the following beta functions (describing how couplings change with energy scale μ):

$$\beta_\gamma = \mu\frac{d\gamma}{d\mu} = -\frac{\kappa^2}{24\pi^2}$$

$$\beta_\kappa = \mu\frac{d\kappa}{d\mu} = \frac{3\kappa^3}{16\pi^2}$$

$$\beta_\lambda = \mu\frac{d\lambda}{d\mu} = \frac{\kappa^2 m^2}{8\pi^2} \quad \text{(where } m \text{ is fermion mass)}$$

- **Renormalizability:** The fact that only these dimension-4 parameters get renormalized (and no new types of interactions are generated at one loop) suggests the theory is likely perturbatively renormalizable, similar to well-understood theories like scalar QED.

- **Stability (No Ghosts):** The beta function for the stiffness γ is negative ($\beta_\gamma < 0$). This implies that γ increases as the energy scale decreases (running towards the infrared). If γ is positive at some high energy scale (e.g., the Planck scale), it will remain positive at lower energies. This is crucial, as a negative γ would lead to a negative kinetic energy term, signaling the presence of unphysical "ghost" states that violate unitarity. The negative beta function helps ensure the stability of the quantum theory.

E.3 Higher Derivatives and Ostrogradsky Instability

A common problem in modified gravity theories is the appearance of higher-order time derivatives in the equations of motion, leading to Ostrogradsky instabilities. Does this happen when quantizing the S_{ent} EFT on a curved background?

- **Heat-Kernel Method:** Analysis using the heat-kernel expansion for the one-loop effective action on a general curved spacetime reportedly shows that the quantum divergences generated require counterterms proportional to standard geometric invariants (like $\sqrt{-g}R$ and $\sqrt{-g}R^2$) and renormalizations of the existing terms in the S_{ent} action.

- **No Higher Derivatives for S_{ent}:** Crucially, this analysis reportedly shows that no higher-derivative kinetic terms for S_{ent}, such as $(\nabla^2 S_{\text{ent}})^2$, are generated by loop corrections. The kinetic term remains second-order in derivatives.

- **Stability:** This ensures that the EFT avoids the Ostrogradsky instability associated with higher-derivative theories, further supporting its mathematical consistency.

E.4 Strong-Field Stability near Horizons

How does the theory behave in extreme gravitational environments, like near black holes?

- **Mode Analysis:** Numerical analysis of the S_{ent} field's equation of motion ($\Delta_S S_{\text{ent}} = \ldots$, where Δ_S includes the kinetic operator and effective mass terms) in fixed black hole backgrounds (Schwarzschild, Kerr) reportedly shows no unstable modes (1). Specifically, there are no solutions with negative squared frequencies (tachyonic instabilities) or exponential growth in time (bound state instabilities).

- **Conclusion:** The EFT appears to remain stable and well-behaved even in the strong curvature regimes found near black hole horizons.

Overall Consistency Conclusion: Based on these reported checks (renormalization behavior, absence of higher derivatives, stability in strong fields), the Entropic Scalar EFT appears to be a mathematically consistent, perturbatively stable, and potentially renormalizable quantum field theory, making it a viable candidate for describing physics beyond the Standard Model and General Relativity.

F Conclusion: The Layered Picture

This appendix has delved into the theoretical foundations supporting the Entropic Scalar Effective Field Theory introduced by Chinitz (2025). We explored its internal structure, its potential emergence from underlying quantum gravity frameworks like Group Field Theory and Information-Complete Quantum Field Theory, the intriguing possibility of deriving gauge forces from similar principles, and its mathematical consistency as a quantum field theory.

A coherent, layered picture emerges:

1. At the most fundamental **UV (Ultraviolet) level**, reality might be described by theories like GFT or ICQFT, where spacetime and matter are deeply intertwined manifestations of quantum information and entanglement, governed by parameters like the GFT mass scale α or the ICQFT volume entropy constant μ.

2. In an appropriate **coarse-grained or continuum limit**, these fundamental theories give rise to the **Entropic Scalar EFT**. This intermediate description captures the collective dynamics of entanglement deficits through the scalar field $S_{\text{ent}}(x)$, characterized by effective parameters like the stiffness γ, the matter coupling κ, and the crucial mass-per-bit constant κ_m. This EFT serves as the essential bridge connecting the abstract quantum gravity realm to observable physics.

3. At the **IR (Infrared) or macroscopic level**, this EFT reproduces the successes of General Relativity where appropriate but also provides unified explanations for diverse **observable phenomena**. These include gravity itself (as an entropic effect), inertial mass (via $m = \kappa_m S_{\text{ent}}$), the flow and arrow of time (via entropic time dilation), phenomena usually attributed to dark matter (via S_{ent} gradients mimicking gravitational potentials) and dark energy (via the entropic lapse function mimicking cosmic acceleration), and potentially even the gauge forces of the Standard Model.

The fundamental constant κ_m plays a pivotal role, linking the mass scale of particles in the observable world to the entanglement parameters (α, μ) of the underlying UV theories. This framework, therefore, presents a compelling vision for unification, suggesting that gravity, mass, time, cosmology, and perhaps even gauge interactions all emerge naturally from the structure and dynamics of quantum entanglement in the universe.

References

[1] J. Chinitz, *Entanglement Entropy: Unifying the Quantum Origins of Gravity, Mass, Time, and Cosmic Structure* (2025).

[2] J. Liu *et al.*, "Emergent Gravity from the Entanglement Structure in Group Field Theory," arXiv:2304.10865 (2023).

[3] Z.-B. Chen, "Quantum Information Dynamics of Spacetime and Matter," arXiv:1412.3662 (2023).