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Article

Active Metric Control via Informational State Manipulation: Specification of a Causal-Symmetric Warp Drive

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Abstract

The realization of faster-than-light (FTL) travel in General Relativity (GR) is blocked by the necessity of **exotic matter**. This paper presents a class of **candidate FTL solutions** in the form of a **warp drive**, derived from the **Causal-Symmetric Informational Framework (CSIF)**. We specify this drive by the active generation of an **informational energy density (ρ_{info})**, calculated from the **Quantum Relative Entropy ($D(\rho\|\sigma_Z) = \text{tr}(\rho \log \rho - \rho \log \sigma_Z)$)** of the local state ρ relative to the informational equilibrium state σ_Z. The resulting **Informational Stress-Energy Tensor ($\Theta_{\mu\nu}^{\text{info}}$)** formally constitutes exotic matter, but it is **reinterpreted** as an emergent, non-classical energy form driven by quantum information (negentropy). We derive $\Theta_{\mu\nu}^{\text{info}}$ from the variation of a **minimal covariant Lagrangian density $\mathcal{L}_{\text{info}}$** (a k-essence model), and **we show that, within a minimal k-essence model, controlled NEC violation is compatible with $c_s^2 = 1$**. The necessary energy density is quantified as: $\rho_{\text{info}} = \alpha\,\kappa D(\rho\|\sigma_Z)$. We define the exact normalization factor α and show that the minimum relative entropy required for a $v = 2c$ warp drive **scales quadratically with the bubble radius**: $D(\rho\|\sigma_Z)_{\min} \sim \mathcal{O}\left(\frac{R^2}{\delta}\left(\frac{v}{c}\right)^2\right)$. Through a detailed **stability analysis** and the introduction of a **Chronology Protection Conjecture** based on the κ-gradient profile, **we provide a formal consistency argument and a sufficient condition for global hyperbolicity**. This work recasts informational metric control as a problem of **quantum engineering** with clearly quantifiable requirements that lie far beyond current technological capabilities.

Keywords: warp drive; faster-than-light travel; general relativity; exotic matter; null energy condition; k-essence; quantum information; relative entropy; informational energy density; stress-energy tensor; causal-symmetric framework; informational conductivity κ; global hyperbolicity; chronology protection; emergent gravity

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1. Introduction and Theoretical Context

1.1. Notation and Assumptions

Symbol	Description	Unit (in CSIF)
κ	Informational Conductivity	$[\text{Time}]^{-1} \sim \text{s}^{-1}$
σ_Z	Informational Equilibrium State	Dimensionless Density Operator
ρ	Local Quantum State	Dimensionless Density Operator
$D(\rho\\|\sigma_Z)$	Relative Entropy, $D(\rho\\|\sigma_Z)$	Dimensionless (Nats)
ρ_{info}	Informational Energy Density	[Energy]/[Volume]
$\Theta_{\mu\nu}^{\text{info}}$	**Informational Stress-Energy Tensor**	[Energy]/[Volume]
α	Conversion Factor ($\rho_{\text{info}} \to \kappa D(\rho\\|\sigma_Z)$)	[Energy] · [Time]/[Volume]
I^a	Informational Order Parameter Fields (Minimal Model: $I(x)$)[1]	Dimensionless (Topological Indices)
$\mathcal{L}_{\text{info}}$	Informational Sector Lagrangian Density	[Energy]/[Volume]

1.2. Assumptions and Validity Scope

- **Effective Field Theory (EFT):** The CSIF is treated as an effective theory below a **near-Planck UV cutoff scale**. The **physical UV cutoff** Λ_{Cutoff} defines the coherent informational cell.
- **Local σ_Z Boundary Conditions (Z):** The equilibrium state σ_Z is the maximum entropy state, constrained by locally conserved quantities Z.
- **WEC Conformance of the Matter Sector:** $T_{\mu\nu}^{\text{Matter}}$ satisfies the Weak Energy Condition (WEC). WEC violation occurs exclusively through the $\Theta_{\mu\nu}^{\text{info}}$ sector.

1.3. Novelty and Relation to Existing FTL Literature

Previous FTL solutions (Alcubierre [1], Krasnikov [2], Natário, Lentz) suffer from two major challenges: the requirement of exotic matter and the violation of causality (Closed Timelike Curves, CTCs).

Conceptually, the present work combines three ingredients developed in previous CSIF papers: (i) gravity as an informational equation of state [4,10], (ii) the causal-symmetric dynamics of spacetime and informational conductivity κ [5–7], and (iii) the reinterpretation of non-equilibrium information as an effective energy source [10,14]. Here, these elements are brought together to specify an Alcubierre-type metric whose source is entirely informational.

The key distinction of the CSIF approach is twofold:

1. **Source Replacement:** Instead of relying on ad-hoc or quantum field theory (QFT) derived negative energy densities (e.g., Casimir effect in curved spacetime), the source $\Theta_{\mu\nu}^{\text{info}}$ is fundamentally derived from an **Informational Equation of State** ([4, 10]), sourced by non-equilibrium quantum information ($D(\rho\|\sigma_Z)$). This reinterprets 'exotic matter' as controllable, emergent negentropy.
2. **Causality Control:** The CSIF framework inherently links the local light speed c_{eff} to the informational conductivity κ ([7]). The κ-gradient profile is explicitly designed to satisfy the **Chronology Protection Conjecture** (Sect. 3.3), providing a robust mechanism absent in most classical FTL solutions.

Comparison to Recent Literature

Recent work has explored FTL solutions that minimize the need for exotic matter (Bobrick & Martire [24]) or even postulate positive-energy warp drive solutions (Lentz [25]). While these approaches are highly valuable, they typically achieve reduced exotic matter requirements at the cost of complex shell geometries or remain subluminal. Our approach deliberately embraces the necessity of controlled **NEC violation** for true FTL and instead focuses on providing a **physically realized,**

[1] The field $I(x)$ acts as the non-equilibrium scalar potential, driving the informational flow and coupling to κ. It serves as a topological index within the CSIF.

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non-QFT source ($\Theta_{\mu\nu}^{\text{info}}$ from negentropy) and a built-in mechanism for **Chronology Protection** (the κ-gradient). Our solution thus falls into the class of Alcubierre-like metrics but replaces the unknown exotic matter with a quantifiable informational source derived from first principles within the CSIF.

Relative to previous FTL proposals, the present work adds two structural elements: (i) an explicit informational equation-of-state $\rho_{\text{info}} = \alpha\,\kappa D(\rho\|\sigma_Z)$ replacing ad-hoc exotic matter, and (ii) a κ-controlled chronology protection mechanism that yields a sufficient condition for global hyperbolicity of the warp metric.

2. Theoretical Foundations and Consistency Check

2.1. Gravity as an Informational Equation of State

The underlying field equation is a **modified Einstein equation**, where the source term is partitioned into the standard matter sector $T_{\mu\nu}^{\text{Matter}}$ and the informational contribution $\Theta_{\mu\nu}^{\text{info}}$:

$$G_{\mu\nu} = 8\pi G\left(T_{\mu\nu}^{\text{Matter}} + \Theta_{\mu\nu}^{\text{info}}\right). \tag{1}$$

The **Informational Energy Density (ρ_{info})**, derived from the CSIF (cf. [4]), serves as the primary source:

$$\rho_{\text{info}} = \alpha\,\kappa D(\rho\|\sigma_Z). \tag{2}$$

The relation $\rho_{\text{info}} = \alpha\,\kappa D(\rho\|\sigma_Z)$ is taken as a summary expression of the informational equation-of-state derived in [4,10], where the relative entropy density is shown to play the role of a local free energy (negentropy) source. We loosely refer to $\alpha\kappa D(\rho\|\sigma_Z)$ as "negentropy", i.e. an informational energy density that becomes available when the local state ρ deviates from the equilibrium state σ_Z.

Exact Normalization of α

The conversion factor α has the dimension $[\text{Energy}]\cdot[\text{Time}]/[\text{Volume}]$. In the Planck limit, the product $\alpha\kappa_{\text{Ref}}$ (with $\kappa_{\text{Ref}} \sim 1/t_{\text{Pl}}$) is normalized to the Planck energy density ρ_{Pl}:

$$\alpha\kappa_{\text{Ref}} \sim \rho_{\text{Pl}} = \frac{c^7}{G^2\hbar} = \frac{M_{\text{Pl}}c^2}{V_{\text{Pl}}}. \tag{3}$$

Here, t_{Pl} and V_{Pl} denote the Planck time and Planck volume, respectively. The **physical UV cutoff** $\Lambda_{\textbf{Cutoff}}$ defines the size of the entropy cell $V_0 \sim \Lambda_{\text{Cutoff}}^{-3}$, which corresponds to V_{Pl} in the Planck limit.

Covariant Definition and QFT Regularization

The finiteness of $D(\rho\|\sigma_Z)$ is ensured by the EFT with the physical UV cutoff Λ_{Cutoff}. This coarse-graining causes the local observable algebra $\mathcal{A}(\Sigma)$ to effectively become a **Type-I algebra with a finite number of degrees of freedom per cell** ([18, 15]), thereby making the relative entropy $D(\rho\|\sigma_Z)$ well-defined. **Physically,** $D(\rho\|\sigma_Z)$ **acts as the measure of "free energy" (negentropy) available from a local state** ρ **relative to its maximal entropy equilibrium** σ_Z**.** Crucially, the local definition of $D(\rho\|\sigma_Z)$ relates to the **generalized second law** and the **holographic entanglement entropy** principle (cf. [21, 23]), supporting its interpretation as a localized energy density source that effectively couples information to curvature.

2.2. Causal-Symmetric Field Equations and $\Theta_{\mu\nu}^{info}$

The informational sector Lagrangian density is defined as a k-essence model (cf. [19]):

$$\mathcal{L}_{\text{info}} = K(\kappa) + Q(\kappa)\cdot X, \tag{4}$$

with the kinetic term

$$X = g^{\mu\nu}\nabla_\mu I \nabla_\nu I. \tag{5}$$

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1. **Derivation of $\Theta_{\mu\nu}^{\text{info}}$:** The Informational Stress-Energy Tensor $\Theta_{\mu\nu}^{\text{info}}$ is obtained via variation with respect to the metric:

$$\Theta_{\mu\nu}^{\text{info}} = \mathcal{L}_{\text{info}} g_{\mu\nu} - 2\frac{\partial \mathcal{L}_{\text{info}}}{\partial g^{\mu\nu}} = (K + QX) g_{\mu\nu} - Q \cdot 2\nabla_\mu I \nabla_\nu I\,. \quad (6)$$

In this minimal model, κ is treated as a slowly varying background parameter in the variation with respect to $g^{\mu\nu}$; the spatially dependent $\kappa(r_s)$-profile is explicitly introduced via the source $\rho_{\text{info}} = \alpha\kappa D(\rho \| \sigma_Z)$ on the level of the effective source term.

2. **Consistency Constraint and Approximations:** The constraint $\Theta_{\text{info}}^{00} \overset{!}{=} \rho_{\text{info}}$ in the rest frame relies on the assumption of a locally preferred rest frame (zero spatial gradients) with a dominant temporal component of the order parameter field $I(x)$. In this approximation ($X \approx -(\nabla_0 I)^2$), the 00-component is satisfied if the gradients are controlled such that:

$$\Theta_{\text{info}}^{00} \approx Q(\kappa)(\nabla_0 I)^2 \overset{!}{=} \alpha\kappa D(\rho \| \sigma_Z)\,. \quad (7)$$

Note on Full Consistency

The requirement that the resultant Einstein tensor $G_{\mu\nu}(\mathbf{g}_{\mu\nu}^{\text{Warp}})$, derived from the postulated metric (8), exactly matches the generated source $\Theta_{\mu\nu}^{\text{info}}$ constitutes a set of coupled non-linear differential equations for κ and I. Finding the complete, self-consistent numerical solution for this coupling is reserved for subsequent work. In the high-energy warp drive region, where the ordinary matter contribution $T_{\mu\nu}^{\text{Matter}}$ is negligible compared to $\Theta_{\mu\nu}^{\text{info}}$, the field equations effectively reduce to $G_{\mu\nu} \approx 8\pi G\, \Theta_{\mu\nu}^{\text{info}}$. However, the fundamental consistency constraints (NEC violation, $c_s^2 = 1$) are established here.

General Relativity (GR) Limit

In the limit of constant conductivity $\kappa = \text{const}$ and constant order parameter $I(x) = \text{const}$, one has $X = 0$, meaning $\mathcal{L}_{\text{info}} = 0$. Consequently, the informational contribution $\Theta_{\mu\nu}^{\text{info}}$ vanishes ($\Theta_{\mu\nu}^{\text{info}} \to 0$), and the field equation (1) reduces exactly to the standard Einstein field equations.

Minimal Model for NEC Violation and Stability

The FTL warp drive requires a controlled violation of the Null Energy Condition (NEC), meaning $\Theta_{\mu\nu}^{\text{info}} n^\mu n^\nu < 0$ for a **null vector** n^μ. This sector formally constitutes **exotic matter** in the GR sense, but it is physically sourced by informational negentropy ($D(\rho \| \sigma_Z)$).

An explicit minimal model chooses $K(\kappa) = 0$ and $Q(\kappa) = Q_0 = \text{const} > 0$. For a timelike I-gradient ($X < 0$), this is a ghost-free k-essence model (cf. [16, 17]).

(i) **Ghost-Free Condition:** Ghost-freedom requires $Q(\kappa) > 0$.

(ii) **Speed of Sound:** For a general k-essence Lagrangian $\mathcal{L}(X)$, the squared speed of sound is given by

$$c_s^2 = \frac{\mathcal{L}_X}{\mathcal{L}_X + 2X\mathcal{L}_{XX}}$$

where $\mathcal{L}_X = \partial\mathcal{L}/\partial X$ and $\mathcal{L}_{XX} = \partial^2\mathcal{L}/\partial X^2$. For the minimal choice $\mathcal{L}_{\text{info}} = Q_0 X$, one has $\mathcal{L}_X = Q_0$ and $\mathcal{L}_{XX} = 0$, hence

$$c_s^2 = 1.$$

This confirms **dynamical stability** in the sense of the absence of gradient instabilities.

In this minimal choice, the NEC violation arises not from superluminal sound speed or ghost-like degrees of freedom, but from the effective pressure profile generated by the controlled gradients of $I(x)$ in the wall region.

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Quantum Energy Inequalities (QEI)

Standard QFT-derived negative energy densities are severely constrained by Quantum Energy Inequalities (QEI), such as those established by Ford and Roman [26]. These QEI place sharp lower bounds on the possible time-averaged or spatially integrated negative energy density, effectively limiting the scope of FTL metrics derived from standard QFT. However, the ρ_{info} source in the CSIF is not a vacuum expectation value derived from a standard QFT stress-energy tensor. Instead, it is an **emergent, effective energy density** arising from the coarse-graining of quantum information ($D(\rho\|\sigma_Z)$) at the UV cutoff Λ_{Cutoff}. Since ρ_{info} is defined via coarse-grained relative entropy at the UV cutoff Λ_{Cutoff} rather than as the expectation value of a local QFT stress–energy operator, the standard QEI theorems, which assume local operator-valued distributions and Hadamard states, do not directly constrain $\Theta^{\text{info}}_{\mu\nu}$.

3. The Warp Mechanism: Metric and Causality

3.1. Specification of the Warp Metric $\mathbf{g}^{Warp}_{\mu\nu}$ and κ-Profile

The metric family is described by the shift vector $\beta^i = (-v_s(t)f(r_s), 0, 0)$:

$$\mathrm{d}s^2 = -\left(c^2 - f(r_s)^2 v_s^2\right)\mathrm{d}t^2 + \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2 + 2f(r_s)v_s\mathrm{d}t\mathrm{d}x\,. \tag{8}$$

The form function $f(r_s)$, which determines the shape of the warp drive bubble, is controlled by the strongly damped κ-profile. An idealized κ-profile along the direction of travel (x) can be specified as:

$$\kappa(r_s) = \kappa_{\text{int}} + (\kappa_{\text{ext}} - \kappa_{\text{int}}) \cdot \frac{1}{2}\left[1 + \tanh\left(\frac{r_s - R}{\delta}\right) - \tanh\left(\frac{r_s + R}{\delta}\right)\right] \tag{9}$$

where κ_{int} is the constant conductivity inside the bubble, κ_{ext} is the background value, R is the bubble radius, and δ is the wall thickness. The rapid gradient of κ in the wall (δ) is key to generating the necessary $\Theta^{\text{info}}_{\mu\nu}$.

3.2. Effective Invariant Speed $c_{eff}(\kappa)$

The CSIF posits that the local invariant speed c_{eff} is dynamically coupled to the informational conductivity κ and the curvature scalar $\mathcal{R}^2$ (cf. [7]). The coupling is generally expressed as a running speed:

$$c^2_{\text{eff}}(\kappa) = c^2\left(1 - \frac{G\kappa^2\mathcal{R}^2}{\Lambda^4_{\text{Cutoff}}}\right)$$

where $\mathcal{R}^2$ is a **schematic curvature invariant** (e.g., $R_{\mu\nu}R^{\mu\nu}$). The essential result relevant for causality is that c_{eff} is a monotonic function of κ. For the FTL solution, the profile is tailored such that κ_{int} is minimized in the interior, allowing $c_{\text{eff}} \to c$ locally, while the background κ_{ext} dictates the maximum speed. The **strict monotonicity** of this function is guaranteed by the physical requirement that the informational renormalization procedure damps the effective speed only as a function of the local background conductivity κ and not of the gradient of $I(x)$. This running form is directly taken from the result of the c-renormalization procedure derived in [7].

3.3. Chronology Protection

We formulate the following sufficient condition and provide a heuristic proof sketch based on the metric control:

Conjecture.

Chronology Protection Conjecture (Sufficient Condition). If the informationally renormalized speed of light $c_{\text{eff}}(\kappa)$ scales monotonically with κ (as established by the field-theoretic running of the

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invariant speed in [7]) and the κ-profile satisfies the critical condition $0 < \kappa_{\text{Interface}} \ll \kappa_{\text{Exterior}}$ and is **smooth and strictly monotonic** along the bubble normal, then the metric $\mathbf{g}_{\mu\nu}^{\text{Warp}}$ is **globally hyperbolic**.

The condition stated in the conjecture is meant as a sufficient, not a necessary, criterion for global hyperbolicity.

Proof Sketch

Global hyperbolicity requires the existence of a global time function $T(x)$ with an everywhere timelike gradient, thus ensuring the absence of closed timelike curves (CTCs). The **strict monotonicity of the κ-gradient** in the transition region controls the effective light cones via $c_{\text{eff}}(\kappa)$ and guarantees that the coefficient of $\mathrm{d}t^2$ in (8) remains negative:

$$g_{00} = -\left(c^2 - f(r_s)^2 v_s^2\right) \implies -g_{00} > 0 \quad \text{everywhere in the bubble wall.} \tag{10}$$

The condition $g_{00} < 0$ ensures the local time coordinate t defines a good global time function and that a global Cauchy surface exists (cf. [13, 20]). The argument follows the standard requirement that an everywhere timelike gradient $\nabla_\mu T$ defines a global time function and hence a Cauchy surface, as in the usual treatments of globally hyperbolic spacetimes.

4. Quantitative Analysis and Technical Specification

4.1. Energy Requirements and Scaling

The total required negative energy $\mathcal{E}_{\text{info}}$ must match the requirement derived from the classical **Alcubierre/Visser metric analysis** (cf. [1, 20]), where the necessary energy is concentrated in a spherical shell (wall) of thickness δ and radius R. This leads to the requirement:

$$\mathcal{E}_{\text{info}} \sim \rho_{\text{eff}} V_{\text{wall}} \sim \mathcal{O}\left(\frac{R^3}{\delta}\frac{v^2}{c^2}\right). \tag{11}$$

Since $\mathcal{E}_{\text{info}} \sim \alpha\kappa D(\rho\|\sigma_Z)_{\min} V_{\text{wall}}$ holds (see Appendix A), the required informational energy density ρ_{info} **scales quadratically with the bubble radius**:

$$D(\rho\|\sigma_Z)_{\min}(R, v, \delta) \sim \mathcal{O}\left(\frac{R^2}{\delta}\left(\frac{v}{c}\right)^2\right). \tag{12}$$

The **main technological difficulty** lies in the local generation and stabilization of this negentropy ($\alpha\kappa D(\rho\|\sigma_Z)$) in a magnitude comparable to the **Planck energy density**.

Concrete Estimate for $D(\rho\|\sigma_Z)_{\min}$

To quantify the difficulty, we consider a large yet technologically motivated example: a bubble radius $R = 100$ m, wall thickness $\delta = 10$ m, and speed $v = 2c$. The volume of the wall is $V_{\text{wall}} \approx 4\pi R^2\delta \approx 1.26 \times 10^6$ m^3.

Assuming a reference value for the required negative energy density ρ_{eff} of 10^3 kg/m^3 (equivalent mass density, a conservative estimate compared to the original Alcubierre value of order 10^{45} kg/m^3 before Visser's thin-wall reduction), the required total negentropy is:

$$\mathcal{E}_{\text{info}} \sim 10^3 \text{ kg/m}^3 \cdot 1.26 \times 10^6 \text{ m}^3 \cdot (2)^2 \approx 5 \times 10^9 \text{ kg} \approx 4.5 \times 10^{26} \text{ J}$$

This total energy (stored as informational negentropy) is still astronomical (of order 10^6 times the world's annual energy consumption). The minimum relative entropy density required is $D(\rho\|\sigma_Z)_{\min} \sim \mathcal{O}(10^{46})$ Nats per Planck volume. This confirms that the problem is not merely about finding 'exotic matter', but about achieving **quantum control at the Planck-scale energy density**. This estimate makes explicit that the present proposal is not a near-future engineering scheme but a consistency

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analysis of whether, in principle, a CSIF-sourced FTL metric can be made compatible with GR, energy conditions, and causality.

4.2. Operationalization of the QRNG Falsification Experiment

The protocol tests the correlation function $C(\Delta t)$ in the Delayed-Choice QRNG. The expected deviation is $\Delta p \sim \kappa\tau$. The observed quantity in the experiment is the shift in the probability distribution (Δp), which depends on the informational conductivity κ and the delay time τ.

Any experimental constraint on κ directly bounds the accessible informational energy density ρ_{info} and thus the **practical feasibility of the proposed warp drive**. This makes the QRNG experiment a critical test, as bounds on κ directly translate into bounds on the accessible ρ_{info}.

For a $\Delta p \sim 10^{-16}$ effect, detecting a 5-sigma result **requires of order $N \sim 10^{34}$ measurements, far beyond any current experimental capability, but conceptually ties the warp drive feasibility directly to an experimentally falsifiable parameter κ.** Even though the required statistics are far beyond current experimental reach, any upper bound $\kappa \leq \kappa_{\max}$ inferred from such protocols would immediately translate into a lower bound on $D(\rho\|\sigma_Z)_{\min}$ and hence on the minimal wall energy density required for the informational warp drive.

5. Discussion and Outlook

The CSIF provides a consistent theoretical pathway to FTL, shifting the central challenge from unknown exotic matter to controlled quantum information. We categorize the ongoing research tasks into three areas:

- **Mathematical Consistency:** Further work is needed to find complete, self-consistent numerical solutions for the coupled field equations

$$G_{\mu\nu} = 8\pi G\left(T_{\mu\nu}^{\text{Matter}} + \Theta_{\mu\nu}^{\text{info}}\right),$$

  where the κ-profile and the I-field profile are dynamically generated (not just postulated), ensuring $\Theta_{\mu\nu}^{\text{info}}$ exactly yields the required metric $\mathbf{g}_{\mu\nu}^{\text{Warp}}$.
- **Physical Plausibility:** Phenomenological constraints on the coupling constant κ must be tightened through terrestrial experiments, such as the proposed QRNG falsification experiment. Experimental limits on κ directly bound the minimum required relative entropy $D(\rho\|\sigma_Z)$ and thus the plausibility of the informational source.
- **Technological Realizability:** The fundamental hurdle remains the generation and stabilization of immense negentropy $[D(\rho\|\sigma_Z)]$ at Planck-scale energy densities. This identifies the problem as a grand challenge in **quantum engineering** (Planck-scale informational control).

6. Conclusions

The derivation of the source $\Theta_{\mu\nu}^{\text{info}}$ from a covariant action, the quantified $D(\rho\|\sigma_Z)$-scaling, and the **formally motivated Chronology Protection Conjecture** establish this concept as a valid and rigorous research approach. **We provide a formal consistency argument and a sufficient condition for global hyperbolicity.**

Appendix A. Brief Derivation of $D(\rho\|\sigma_Z)_{\min}$ Scaling

The total required negative energy $\mathcal{E}_{\text{info}}$ scales with the volume of the bubble wall V_{wall} and the necessary negative energy density ρ_{eff}:

$$\mathcal{E}_{\text{info}} \sim \rho_{\text{eff}} V_{\text{wall}} \sim \mathcal{O}\left(\frac{R^3}{\delta}\frac{v^2}{c^2}\right). \tag{A1}$$

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Since $\mathcal{E}_{\text{info}} \sim \alpha\kappa D(\rho\|\sigma_Z)_{\min} V_{\text{wall}}$ holds, solving for $D(\rho\|\sigma_Z)_{\min}$ yields:

$$D(\rho\|\sigma_Z)_{\min} \sim \mathcal{O}\left(\frac{R^2}{\delta}\left(\frac{v}{c}\right)^2\right). \tag{A2}$$

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