Holographic Closure Capacity and Transactional Exhaust

A Conjectural Extension of the Selective Transient Field Framework

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> **STATUS — CONJECTURE PROGRAM.** This paper is an architectural proposal, not a theorem-grade result: it states hypotheses, the theorem chain that would be required to establish them, and the falsifiers that would reject them. Its claim ledger (§10) assigns every statement its status, including the false ones. It sits downstream of the four results named in §1 and modifies none of them. Nothing in it may be cited as established STF physics.

Abstract

The Selective Transient Field (STF) framework proposes that a physical history becomes actual through topological closure of retarded and advanced causal sectors. Its Closure–Capacity Correspondence further proposes that closure is possible only when the available transactional channel capacity is at least as large as the unresolved information that must be stabilized. This paper asks whether that correspondence can be combined with horizon entropy to define a finite universal closure capacity, and whether failure to close can leave a gravitating but transactionally inaccessible residue.

The result is a disciplined conjecture program rather than a completed theory. The Gibbons-Hawking entropy of an asymptotic de Sitter horizon constrains the number of distinguishable gravitational states under its usual assumptions. It does not by itself count transactions, measure a causal channel, or establish that the cosmic ledger fills monotonically. The STF normalization $4\pi^2$, the integer winding number w, one Shannon bit, and a thermodynamic entropy increment are mathematically different quantities. Converting one into another requires a physical coding theorem that has not yet been supplied.

We therefore formulate the Holographic Closure-Capacity Hypothesis conditionally. A finite transaction bound follows only if each independently distinguishable closure writes a non-reusable physical record to a finite boundary algebra. We then formulate the Transactional Exhaust Hypothesis: a failed or inaccessible closure sector may retain a conserved stress tensor while decoupling from ordinary record-forming interactions. Merely gravitating is not sufficient to reproduce cold dark matter. A viable exhaust sector must derive $w \simeq 0$, negligible sound speed and anisotropic stress, stable clustering, gravitational lensing, and the observed cosmological power spectra. It must also be related explicitly to, or distinguished from, the existing STF ultralight oscillating-scalar dark-matter candidate.

The paper identifies the exact theorem chain needed to turn the proposal into physics: a closure coding map, an accessibility and reuse law for boundary records, a covariant exhaust action, a conservation and transfer law, and a cosmological perturbation analysis. Until those steps are completed, holographic closure capacity and transactional exhaust remain falsifiable architectural hypotheses, not consequences of topological closure.

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1. Scope and dependency firewall

This paper begins downstream of four STF results and does not modify their status:

1. The Clock-Separation Theorem distinguishes the oscillating internal phase from universal temporal ordering.
2. *The Universal Clock Carrier* selects a boundary-conditioned CMC normal as the preferred nonpropagating carrier candidate.
3. The Universal Embedding Principle constructs a Born- and Bell-compatible quantum embedding but does not derive the Born rule.
4. Topological closure supplies a retarded/advanced winding normalization $\int \omega_R \wedge \omega_A = 4\pi^2$, but does not select one outcome from the histories it normalizes.

Nothing in the present conjecture can repair an open universal-to-local gluing theorem, an open CMC existence theorem, or an absent outcome-selection rule. Closure capacity is a proposed additional layer: it asks how much unresolved information a physical boundary channel can stabilize. Transactional exhaust is further downstream: it asks what dynamical residue, if any, remains when that capacity condition fails.

The separation is essential. Horizon thermodynamics must not be used to turn a quantum compatibility result into a Born-rule derivation, and the existence of a gravitating residue must not be inferred from a metaphor about information loss.

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2. The standard holographic input

2.1 De Sitter horizon entropy

For a four-dimensional asymptotic de Sitter spacetime with cosmological constant $\Lambda > 0$, the horizon radius is

$$r_{\mathrm{dS}} = \sqrt{\frac{3}{\Lambda}},$$

and the horizon area is

$$A_{\mathrm{dS}} = 4\pi r_{\mathrm{dS}}^2 = \frac{12\pi}{\Lambda}.$$

The Gibbons-Hawking entropy is therefore

$$S_{\mathrm{dS}} = \frac{k_B c^3 A_{\mathrm{dS}}}{4G\hbar} = \frac{3\pi k_B c^3}{G\hbar\Lambda}.$$

In units $k_B = c = \hbar = 1$,

$$S_{\mathrm{dS}} = \frac{3\pi}{G\Lambda}.$$

If the entropy counts a finite number of distinguishable states, the associated state-space estimate is

$$\ln \dim \mathcal{H}_{\mathrm{dS}} \lesssim \frac{S_{\mathrm{dS}}}{k_B}.$$

This is the legitimate holographic starting point. It is a bound on distinguishable states or boundary information under the assumptions of the de Sitter entropy interpretation.

2.2 What the entropy bound does not say

The same bound does not immediately determine:

- the number of physical events occurring during cosmic history;
- the number of times a finite memory can be reused;
- the complexity or duration of a history encoded by one boundary state;
- the rate at which closure information can be transmitted;
- the entropy written by one STF transaction; or
- whether the asymptotic universe is exactly de Sitter.

A finite state space can support arbitrarily long sequences unless a separate irreversibility or no-reuse law is imposed. Conversely, a single state may encode correlations among many events. Horizon entropy is therefore not a cumulative event counter.

Status. The horizon entropy formula is standard. Its interpretation as an STF transaction budget is not.

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3. Four quantities that must remain distinct

The proposed correspondence involves four objects that are easily conflated.

3.1 Topological normalization

For one completed retarded/advanced torus,

$$\frac{1}{4\pi^2}\int_{T^2_\gamma}\omega_R \wedge \omega_A = 1.$$

The factor $4\pi^2$ normalizes the cup product. It is dimensionless and does not by itself carry units of entropy, channel capacity, or energy.

3.2 Winding number

The integer

$$w \in \mathbb{Z}$$

classifies a homotopy sector. A fixed value $w = 1$ certifies one winding class. A value known in advance carries no Shannon information by itself. Information appears only when a receiver must distinguish among alternative values or histories according to a specified probability distribution.

3.3 Shannon information

For an unresolved set of alternatives with probabilities p_i,

$$H_{\mathrm{unresolved}} = -\sum_i p_i \log_2 p_i.$$

Two equiprobable alternatives require one bit to label. This is the rigorous core of the Theorem of the Unknown. It does not show that nature uses a winding number as that label.

3.4 Thermodynamic entropy

A physical memory reset or irreversible record can carry a thermodynamic cost, but the cost depends on the implementation, temperature, accessibility, and logical operation. A topological label does not become a thermodynamic entropy increment merely because both can be counted.

The missing bridge is thus not a numerical conversion factor. It is a physical map among a homotopy class, a code alphabet, an accessible channel, and a boundary record.

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4. The Closure–Capacity Correspondence

4.1 The schematic inequality

Let $H_{\text{unresolved}}$ denote the information needed to distinguish the globally admissible completions left unresolved by local data. Let C_{closure} denote the usable capacity of the physical channel that anchors or certifies closure. The proposed condition is

$$C_{\text{closure}} \geq H_{\text{unresolved}}.$$

The corresponding margin is

$$M_{\text{cl}} = C_{\text{closure}} - H_{\text{unresolved}}.$$

Within the conjecture:

- $M_{\text{cl}} > 0$ is a supercritical closure regime;
- $M_{\text{cl}} = 0$ is the proposed critical-closure surface; and
- $M_{\text{cl}} < 0$ is an unresolved or non-closing regime.

These inequalities become physical only when both sides are defined for the same channel use, bandwidth, time interval, and logarithmic base.

4.2 Why the data-rate theorem is not yet an STF theorem

In control theory, a data-rate theorem relates stabilization of a specified unstable dynamical system to the capacity of a specified communication channel. The theorem assumes identifiable states, dynamics, messages, channel uses, noise, encoder, decoder, and stabilization criterion.

The STF analogy currently lacks several of these elements:

1. the sender and receiver of the closure record;
2. the physical carrier and its accessible observables;
3. the channel-use interval;
4. the noise and error model;
5. the code mapping histories to records;
6. the dynamical quantity being stabilized; and
7. the covariant observable representing C_{closure}.

The external data-rate theorem can guide the construction, but it cannot be transferred by notation alone.

4.3 The Closure Coding Theorem target

A completed STF theorem would require a map

$$\mathfrak{C} : \mathcal{H}_{\text{admissible}} \longrightarrow \mathcal{A}_{\partial},$$

from admissible global histories to distinguishable elements of a physical boundary algebra $\mathcal{A}_{\partial}$. It would then have to establish:

$$I(\mathfrak{C}) \geq H_{\text{unresolved}},$$

with a covariant accessibility rule and a demonstrated relationship to the STF winding sector. Only then would “one winding supplies one bit” be more than a structural conjecture.

Status. The one-bit label theorem is elementary and exact. The physical winding-to-bit exchange is open.

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5. The Holographic Closure-Capacity Hypothesis

Suppose the following additional premises hold:

1. the terminal boundary algebra has a finite effective state capacity bounded by S_{dS};
2. every independently distinguishable closure writes a physical boundary record;
3. each record consumes a non-reusable entropy increment $\Delta S_{\mathrm{closure}} > 0$;
4. the records cannot be reversibly compressed below that increment; and
5. the same boundary degrees of freedom cannot be reused without erasing a closure distinction required by the final history.

Then a cumulative count would satisfy the conditional bound

$$N_{\mathrm{closure}} \leq \frac{S_{\mathrm{dS}}}{\Delta S_{\mathrm{closure}}}.$$

This implication is valid given the premises. The premises are precisely what remain unproved. In particular, no current STF calculation supplies $\Delta S_{\mathrm{closure}}$, and no theorem says that the global history is stored as a list of separately paid records rather than as one correlated boundary state.

The phrase "the cosmic ledger fills" should therefore be treated as a model, not a consequence of holography. A more conservative possibility is that the boundary algebra bounds simultaneous distinguishability while transactions reuse degrees of freedom or are encoded relationally. These alternatives must be decided by the future closure-coding construction.

Holographic Closure-Capacity Hypothesis. *If completed STF transactions are represented by irreducible, non-reusable records in a finite terminal boundary algebra, then the horizon entropy bounds the number of mutually distinguishable closure records.*

Status. Conditional proposition. Applicability to the universe is open.

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6. Transactional exhaust

6.1 Definition of the hypothesis

Assume a sector requests closure with

$$C_{\mathrm{closure}} < H_{\mathrm{unresolved}}.$$

The capacity conjecture labels the history unresolved, but it does not say what happens dynamically. The Transactional Exhaust Hypothesis adds a new premise: the non-closing sector loses access to ordinary record-forming interactions while retaining a covariantly conserved gravitational source.

Symbolically, let X denote the proposed residue. A consistent effective description requires

$$S_X = \int d^4x \sqrt{-g}\,\mathcal{L}_X, \qquad T^{(X)}_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S_X}{\delta g^{\mu\nu}},$$

and, in the absence of a specified exchange with other sectors,

$$\nabla_\mu T^{\mu\nu}_{(X)} = 0.$$

No such action or transfer law follows merely from the inequality $C < H$.

6.2 Why gravitational persistence is nontrivial

Saying that a failed transaction "continues to curve spacetime" assumes that its stress-energy survives the failure. A genuine theory must explain:

- which variables persist;
- why their energy is positive and conserved;
- whether the failed sector exchanges energy with the active sector;
- how it couples to the universal CMC carrier;
- whether it is local, nonlocal, or boundary-supported; and
- whether it introduces ghosts, gradient instabilities, or acausal modes.

The distinction between participation in universal geometry and participation in local record formation may motivate weak nongravitational coupling. It does not calculate the stress tensor.

6.3 Cold-dark-matter requirements

To reproduce the background kinematics of pressureless matter, the residue must approximately satisfy

$$p_X \simeq 0, \qquad w_X = \frac{p_X}{\rho_X} \simeq 0, \qquad \rho_X \propto a^{-3}.$$

To reproduce perturbative cold dark matter, it must additionally have

$$c^2_{s,X} \simeq 0, \qquad \pi_X \simeq 0,$$

over the cosmologically relevant scales, where c_s^2 is the effective sound speed and π_X the anisotropic stress. It must generate the observed growth of structure, lensing potentials, matter power spectrum, halo abundances, and cosmic microwave background effects.

"Non-interacting and gravitational" is therefore only a qualitative resemblance to dark matter, not a derivation of it.

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7. Relation to the existing STF scalar dark-matter sector

The STF framework already contains an ultralight oscillating scalar with

$$m_s \simeq 3.94 \times 10^{-23}\ \mathrm{eV}/c^2, \qquad \langle w_\phi \rangle \simeq 0,$$

as a dark-matter candidate. Transactional exhaust cannot be added without deciding among three mutually distinct possibilities:

1. **Identity:** the oscillating scalar is the exhaust sector, and closure failure must be shown to produce its mass, phase-space distribution, and stress tensor.
2. **Conversion:** active STF configurations transfer energy into an exhaust component according to a covariant source term Q^ν, with $\nabla_\mu T^{\mu\nu}_\phi = -Q^\nu$ and $\nabla_\mu T^{\mu\nu}_X = Q^\nu$.
3. **Independence:** the exhaust is a second dark component with its own abundance and observational constraints.

Without this choice, the framework risks double-counting the dark matter density. Identity is the most economical option but also the most demanding: the closure mechanism would have to recover the known oscillatory scalar dynamics rather than merely relabel it.

The ultralight mass also means that the scalar is not automatically identical to ideal cold dark matter on every scale. Its gradient or wave pressure must be included when comparing the hypothesis with structure formation. The exhaust proposal cannot erase those existing obligations.

Caveat on option 3 and the Lyman-α closure (added at review, August 2026). The B10 calculation has closed the scalar's all-dark-matter reading at m_s: the Lyman-α bound excludes $f = 1$ by a factor of about 508 (see the Dark Matter paper, §VI.B). Option 3 must not be invoked to evade that closure. A subdominant scalar fraction $f < 1$ was always available by matching a smaller amplitude — no exhaust conjecture is required to obtain it — and what the exhaust would then supply, the remaining dark density, has no derived abundance, equation of state, or sound speed. A partition adopted because it evades a bound is not a partition derived, and would trip this paper's own falsifier 6 (double counting without a derived partition). The connection is recorded here so that it is available if a partition is ever *derived*, and unusable as a shortcut in the meantime.

Status. No identity or conversion theorem presently exists.

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8. Cosmological limits and prohibited shortcuts

The holographic and exhaust conjectures do not currently derive:

- an asymptotic de Sitter phase;
- a present-day equation of state $w_0 = -1$;
- inflation or its perturbation spectrum;
- a time-dependent dark-energy equation of state;
- a solution of the Hubble-constant tension; or
- the observed dark-matter abundance.

Using the de Sitter entropy formula assumes a de Sitter horizon for the purpose of the bound; it cannot then be cited as an independent derivation that the universe must approach de Sitter. Likewise, a boundary capacity metaphor does not determine a Friedmann equation.

Any cosmological claim requires a closed covariant action, background field equations, perturbation equations, stability conditions, initial data, and a likelihood comparison with cosmological observations.

9. Falsifiers and failure conditions

The conjecture program would fail or require major revision under any of the following results:

1. **No closure code:** the STF winding sectors cannot be mapped to accessible boundary records while preserving covariance and the established no-signaling conditions.
2. **Reusable encoding:** closure records can be reversibly encoded or reused without consuming an irreducible entropy increment. Then $S_{\mathrm{dS}}/\Delta S_{\mathrm{closure}}$ is not a transaction count.
3. **No conserved residue:** every covariant completion of $C < H$ transfers or removes the associated stress-energy rather than leaving a gravitational source.
4. **Wrong equation of state:** the derived residue has significant pressure, sound speed, or anisotropic stress on scales where dark matter must cluster.
5. **Instability:** the exhaust action contains ghosts, gradient instabilities, negative energy, or an inconsistent exchange with the CMC carrier.
6. **Double counting:** the exhaust and oscillating scalar independently account for the same observed dark density without a derived partition.
7. **Cosmological exclusion:** the component violates CMB, lensing, structure, halo, or expansion-history constraints.

Until an action exists, these are requirements rather than numerical predictions. Their purpose is to prevent the conjecture from becoming immune to physics.

10. Claim ledger

Statement	Status
The de Sitter horizon has entropy $S_{\mathrm{dS}} = 3\pi k_B c^3/(G\hbar\Lambda)$	standard under de Sitter assumptions
Horizon entropy bounds distinguishable states	standard interpretive result
Horizon entropy counts all transactions in cosmic history	not established
$4\pi^2$ is the STF closure normalization	established within the topological construction
$4\pi^2$ is an entropy cost per transaction	false without a new map
Two equiprobable unresolved alternatives require one bit	theorem
One STF winding supplies one usable bit	conjecture
$C_{\mathrm{closure}} \geq H_{\mathrm{unresolved}}$ is a physical STF threshold	conjecture until the channel is defined
A finite transaction count follows from non-reusable boundary records	conditional proposition
$C < H$ dynamically leaves a conserved gravitating residue	conjecture
Such a residue reproduces cold dark matter	open dynamical program
The residue is identical to the existing oscillating STF scalar	open

Statement	Status
The construction derives $w_0 = -1$, inflation, or the H_0 resolution	false at present

11. Forward derivation program

The work should proceed in dependency order.

1. **Define the boundary algebra.** Specify the observables that distinguish closure records at the terminal macroboundary.
2. **Construct the closure code.** Map admissible histories and winding data to those observables and calculate the accessible mutual information.
3. **Prove or reject non-reuse.** Determine whether closure distinctions consume irreducible boundary capacity or can be encoded reversibly and relationally.
4. **Derive $\Delta S_{\text{closure}}$.** Only after the first three steps can a transaction-count bound be evaluated.
5. **Build the exhaust action.** Introduce no phenomenological dark component until a covariant residue or transfer law follows from the failed-closure dynamics.
6. **Resolve the scalar relation.** Prove identity, conversion, or independence relative to the m_s oscillating scalar.
7. **Perform stability and perturbation tests.** Derive background and linear cosmological equations before numerical parameter fitting.
8. **Confront observations.** Test CMB, large-scale structure, lensing, halo, and expansion data with a frozen likelihood pipeline.

A negative result at any upstream step is informative. In particular, failure of the non-reuse premise would reject the finite-ledger picture while leaving the broader Closure-Capacity Correspondence available in a rate-based form.

12. Conclusion

Holography offers STF a finite state-counting scale, not a ready-made cosmic transaction counter. Topological closure offers a normalized winding class, not a Shannon channel or thermodynamic write cost. The data-rate theorem offers a structural model of stabilization, not a proof that the universe implements the corresponding encoder and decoder. The value of the present proposal lies in placing these ingredients in a single dependency graph without identifying them prematurely.

The Holographic Closure-Capacity Hypothesis becomes meaningful if completed transactions occupy distinguishable, non-reusable records in a finite terminal boundary algebra. The Transactional Exhaust Hypothesis becomes physical if failure of that capacity condition produces a covariantly conserved residue with a derived effective action. Only after both steps can the framework ask whether the residue behaves as dark matter.

The “cosmic ledger” and “garbage collection” metaphors may guide intuition, but the theory must ultimately replace them with a code, a channel, a boundary algebra, and a stress tensor. Until then, transactional exhaust is a speculative extension of STF—clearly motivated, sharply constrained, and deliberately not presented as a theorem.

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