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Copy-Horizon Cosmology from Quantum Information Copy Time: An Operational Infrared Cutoff for Holographic Dark Energy with Testable Signatures

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Copy-Horizon Cosmology from Quantum Information Copy Time: An Operational Infrared Cutoff for Holographic Dark Energy with Testable Signatures

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Abstract

We present a strict, non-circular formulation of a "copy-horizon" infrared (IR) scale $L_{\mathrm{copy}}(t)$ defined operationally from a quantum-information copy time $\tau_{\mathrm{copy}}(L,t)$ by the single criterion $\tau_{\mathrm{copy}}\big(L_{\mathrm{copy}}(t),t\big) = H^{-1}(t)$. The definition requires only mild locality/monotonicity assumptions and does not postulate an *a priori* cosmological IR cutoff (such as the future event horizon). We then combine this operational IR scale with the Cohen–Kaplan–Nelson (CKN) gravitational collapse bound to obtain the L^{-2} energy-density scaling as a consistency constraint, and we formulate "saturation" as a falsifiable mechanism with a severe inequality $c_Q(z) \le 1$. We derive the minimal background consequence $w_Q(t) = -1 + \frac{2}{3}\frac{\dot{L}_{\mathrm{copy}}}{HL_{\mathrm{copy}}}$ and show how a hydrodynamic realization of τ_{copy} yields rigid consistency relations linking expansion, growth, and transient time-of-flight observables.

Keywords: quantum information; operational infrared cutoff; holographic dark energy; cosmology; non-circular derivation; falsifiable signatures

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Scope and Non-Circularity

This paper isolates a single operational input—the *copy time* $\tau_{\mathrm{copy}}(L,t)$—and derives its minimal cosmological consequences *without* introducing an independent cosmological infrared cutoff by fiat. In particular, we do *not* define L_{copy} as the future event horizon. The event-horizon cutoff is used only as a comparator in a dedicated discussion paragraph.

Operational Definition of τ_{copy}

Let A and B be spatially separated regions of a quantum many-body system. At $t = 0$ a local perturbation is applied in A (e.g. by a unitary U_A), yielding two global states $\rho_0(t)$ and $\rho_1(t)$ at time t with reduced states $\rho_{0,B}(t)$ and $\rho_{1,B}(t)$ on B. Given a measurement class $\mathcal{M}_B$ accessible to the receiver, define the optimal distinguishability advantage

$$\Delta_{\mathcal{M}_B}(t;L) \equiv \sup_{M\in\mathcal{M}_B} \left|\mathrm{Tr}\left[M\big(\rho_{1,B}(t) - \rho_{0,B}(t)\big)\right]\right|.$$

For unrestricted $\mathcal{M}_B$ this reduces to the Helstrom distinguishability associated with the trace distance . Fix $0 < \varepsilon < 1$. The copy time is

$$\boxed{\tau_{\mathrm{copy}}(L,t) \equiv \inf\left\{\tau \ge 0:\ \Delta_{\mathcal{M}_B}(\tau;L,t) \ge \varepsilon\right\}.}$$

The *functional form* of τ_{copy} is determined by microscopic dynamics and the choice of $\mathcal{M}_B$; it is not part of the definition. For a complete phenomenology, concrete realizations must be provided (see Sec. 8).

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Brick 1: Defining $L_{\mathrm{copy}}(t)$ with no Model Parameters

We work in a spatially flat FLRW background with Hubble rate $H(t) = \dot{a}/a$. We define the *copy-horizon* scale $L_{\mathrm{copy}}(t)$ as the largest physical separation for which the copy certificate is achievable within one Hubble time:

$$\boxed{\tau_{\mathrm{copy}}\big(L_{\mathrm{copy}}(t), t\big) = H^{-1}(t).}$$

Assuming $\partial_L \tau_{\mathrm{copy}} \geq 0$ and mild regularity, Eq. [eq:brick1] defines $L_{\mathrm{copy}}(t)$ uniquely (locally in time). Differentiating yields the implicit evolution equation

$$\partial_L \tau_{\mathrm{copy}}\big(L_{\mathrm{copy}}, t\big)\, \dot{L}_{\mathrm{copy}} + \partial_t \tau_{\mathrm{copy}}\big(L_{\mathrm{copy}}, t\big) = -\frac{\dot{H}}{H^2}.$$

This step is non-circular: L_{copy} is determined by an operational time criterion, not by an assumed $w(z)$.

Illustrative realizations of $\tau_{copy}(L)$ *(ballistic and diffusive) and the definition* $\tau_{copy}\big(L_{copy}\big) = H^{-1}$*. The intersection determines* $L_{copy}(t)$ *without assuming a cosmological cutoff.*

Brick 2: L^{-2} Scaling from Gravitational Consistency

The CKN bound constrains any effective description in a region of size L: the energy $E \sim \rho L^3$ must not exceed the mass of a black hole of the same size, $M_{\mathrm{BH}}(L) \sim M_{\mathrm{P}}^2 L$. Hence

$$\rho L^3 \lesssim M_{\mathrm{P}}^2 L \quad \Rightarrow \quad \boxed{\rho \lesssim M_{\mathrm{P}}^2 L^{-2}}.$$

Equation [eq:CKN] is not a dark-energy model; it is a consistency constraint. The same L^{-2} scaling underlies the holographic dark energy (HDE) literature, but here it is anchored to the operational scale $L = L_{\mathrm{copy}}(t)$ rather than an *a priori* cosmological horizon choice .

Saturation as Mechanism and a Severe Inequality

We define the copy-horizon component Q by evaluating the CKN-consistent scaling at $L = L_{\mathrm{copy}}(t)$ and allow for a (dimensionless) saturation parameter c_Q:

$$\boxed{\rho_Q(t) = 3\, c_Q^2\, M_{\mathrm{P}}^2\, L_{\mathrm{copy}}(t)^{-2}.}$$

A severe, falsifiable interpretation is

$$\boxed{0 < c_Q(z) \leq 1 \quad \text{for all tested } z,}$$

where $c_Q > 1$ would signal a violation of the gravitational consistency bound at the operational IR scale. In the Supplement we provide an explicit attractor toy-model in which saturation emerges as a stable fixed point.

Logical flow of the strict QICT program: operational τ_{copy} $\rightarrow$ *definition of* L_{copy} $\rightarrow$ *CKN bound* $\rightarrow$ *saturation mechanism and testable consistency conditions.*

Brick 3: Fixing c_Q from $\Omega_{Q,0}$

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Define $\rho_c(t) = 3M_P^2 H(t)^2$ and $\Omega_Q(t) = \rho_Q/\rho_c$. At $t = t_0$ (today), $\rho_{Q,0} = 3M_P^2 H_0^2 \Omega_{Q,0}$. Equating with Eq. [eq:rhoQ] gives

$$\boxed{c_Q^2 = \Omega_{Q,0}\,(H_0\,L_{\text{copy}}(t_0))^2,}$$

so once $L_{\text{copy}}(t_0)$ is obtained from Eq. [eq:brick1], the amplitude is fixed with no multi-parameter cosmological fit.

Minimal Cosmological Consequence: w_Q from Conservation

Assuming no background energy exchange between Q and matter, ρ_Q obeys

$$\dot{\rho}_Q + 3H\big(1 + w_Q\big)\rho_Q = 0.$$

Since $\rho_Q \propto L_{\text{copy}}^{-2}$, we have $\dot{\rho}_Q/\rho_Q = -2\dot{L}_{\text{copy}}/L_{\text{copy}}$, hence

$$\boxed{w_Q(t) = -1 + \frac{2}{3}\frac{\dot{L}_{\text{copy}}(t)}{H(t)\,L_{\text{copy}}(t)}.}$$

Thus w_Q is a consequence once $L_{\text{copy}}(t)$ is determined from τ_{copy}.

Concrete Realizations of τ_{copy} and Rigid Consistency Relations

Ballistic (Causal) Lower Bound

Locality implies a light-cone constraint (Lieb–Robinson or relativity) : no measurement on B can have $\Delta > 0$ before $t < L/v_{\text{LR}}$. Therefore

$$\boxed{\tau_{\text{copy}}(L,t) \geq L/v_{\text{LR}}(t).}$$

Diffusive Hydrodynamic Theorem (Constructive)

Assume a conserved density $n(\mathbf{x},t)$ coupled to the perturbation and a hydrodynamic regime $\partial_t n = D(t)\nabla^2 n$ with slowly varying $D(t)$. For an observable $N_B = \int_B n\,(\mathbf{x})\,d^3x$ in the measurement class, the mean response at distance L is controlled by the diffusive Green's function. Using a severe SNR/Helstrom bound (e.g. via Cauchy–Schwarz and Pinsker-type inequalities) , one obtains asymptotically

$$\boxed{\tau_{\text{copy}}(L,t) = \frac{L^2}{4D(t)}[1 + O(\log L)],}$$

up to subleading logarithmic terms that depend on thresholding and region geometry.

A Hard "Triangle" Test

If the diffusive closure [eq:diffusive] applies on the cosmological effective description, Eq. [eq:brick1] yields

$$\boxed{L_{\rm copy}(t) = 2\sqrt{\frac{D(t)}{H(t)}}.}$$

Consequently, [eq:wQ] becomes a rigid relation between w_Q and the log-derivatives of D and H. The strict program is then to confront a *single* inferred $L_{\rm copy}(z)$ (and $c_Q(z)$) against multiple datasets: expansion $H(z)$ (BAO/SNe/CMB), growth $f\sigma_8(z)$ and lensing, and an independent transient observable (e.g. energy-dependent time-of-flight dispersion $\delta t(E,z)$ if present). The joint compatibility is summarized schematically in Figure 3.

A hard observational test: the same $L_{copy}(z)$ and $c_Q(z) \le 1$ must be compatible with expansion, growth/lensing, and an independent transient observable (if predicted) within the same microphysical closure.

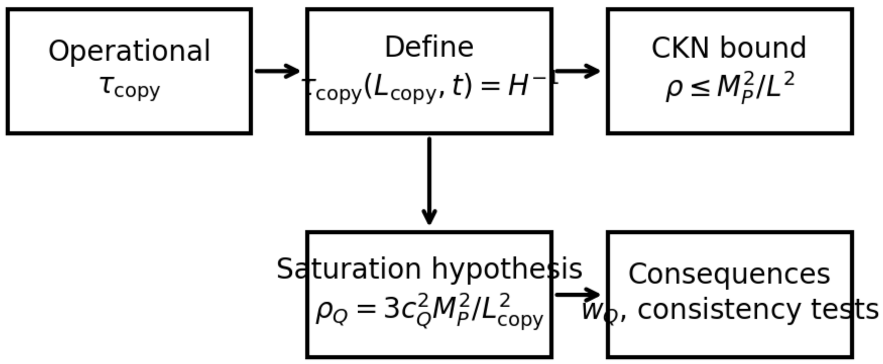

Figure 1. Logical flow of the strict QICT construction: operational copy-time $\rightarrow$ copy-horizon scale $\rightarrow$ gravitational consistency bound $\rightarrow$ saturation hypothesis.

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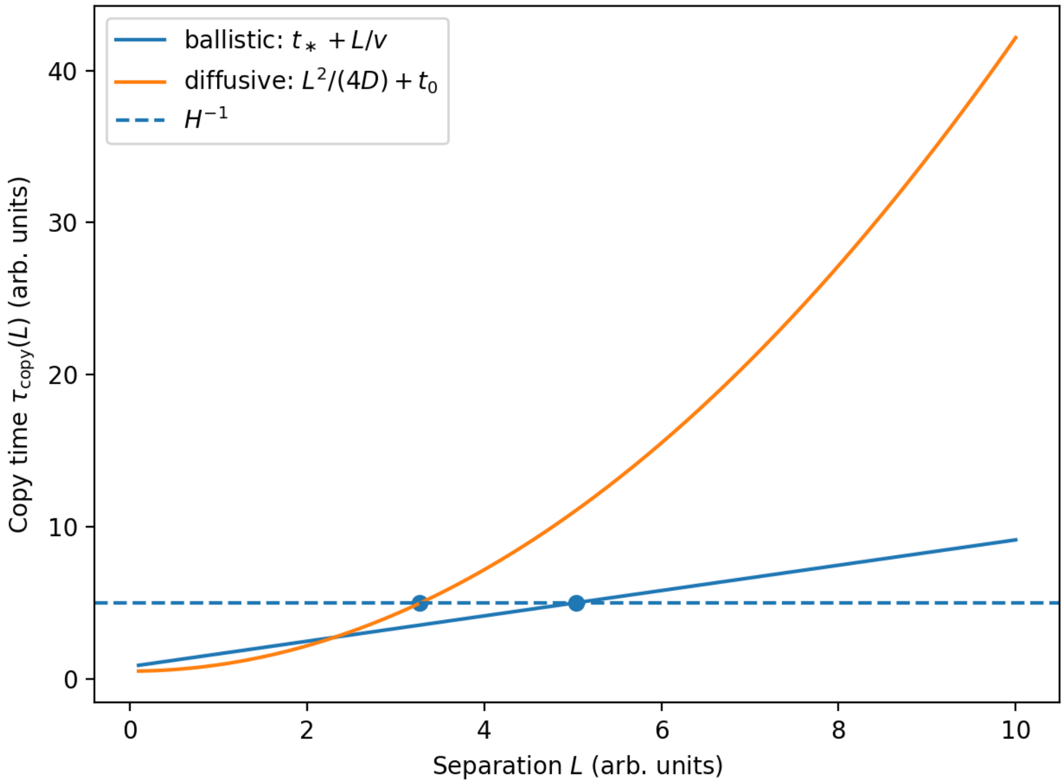

Figure 2. Examples of copy-time scalings (ballistic and diffusive) and the operational definition $\tau_{\mathrm{copy}}(L_{\mathrm{copy}})=H^{-1}$.

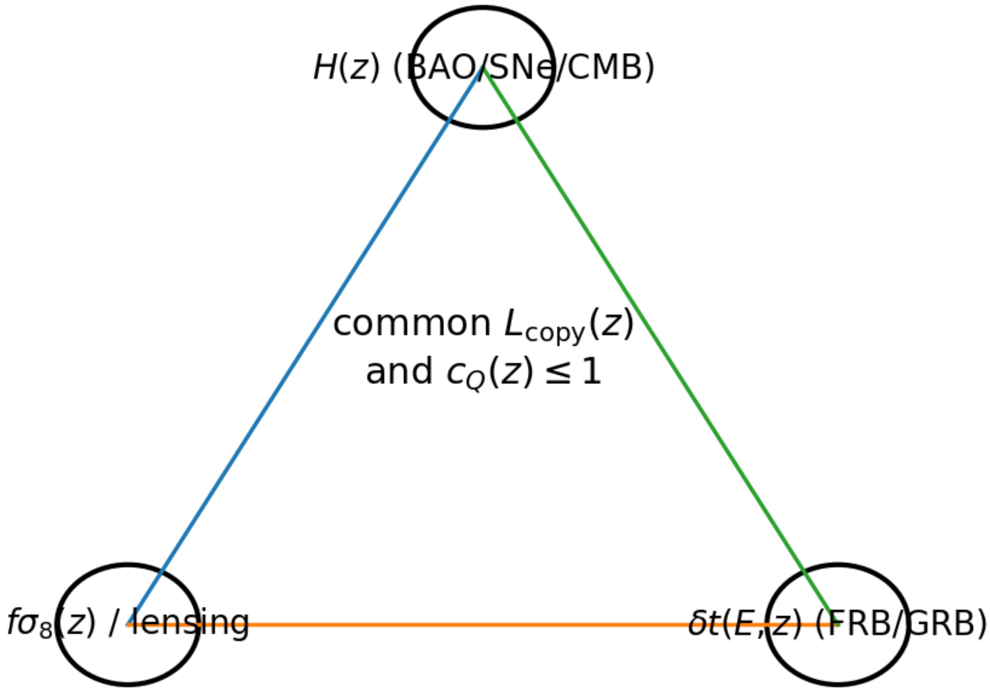

Figure 3. Cross-observable consistency concept linking expansion $H(z)$, equation of state $w_Q(z)$, and an independent transient timing observable.

Minimal Real-Data Sanity Check (Cosmic Chronometers)

To demonstrate that the strict framework can be confronted with *actual* expansion-rate measurements without introducing many phenomenological degrees of freedom, we present a deliberately rigid closure example: (i) the diffusive scaling [eq:diffusive] with *constant* effective diffusivity $D(z) = D_0$, (ii) maximal saturation $c_Q = 1$ motivated by the max-capacity attractor picture in the Supplement, and (iii) spatial flatness with radiation neglected for $z \lesssim 2$.

In this limit, the background expansion becomes parameter-free once (H_0, Ω_{m0}) are fixed. Writing $E(z) = H(z)/H_0$ and $\Omega_{Q0} = 1 - \Omega_{m0}$, the Friedmann equation reduces to a cubic relation

$$\boxed{E(z)^3 - E(z)\,\Omega_{m0}(1+z)^3 - \Omega_{Q0} = 0\,.}$$

We plot the corresponding prediction (normalized to the Planck 2018 baseline values) against a 32-point cosmic-chronometer compilation in Figure 4. This is not advertised as a definitive global fit, but as a minimal, falsifiable closure demonstration that can be systematically upgraded (time-dependent $D(z)$, inclusion of radiation/curvature, joint BAO/SNe/CMB likelihoods).

Minimal real-data sanity check: cosmic-chronometer $H(z)$ points compared to the rigid constant-D diffusive closure with maximal saturation $c_Q = 1$ (no fitted parameters in this illustration; the normalization uses Planck 2018 values).

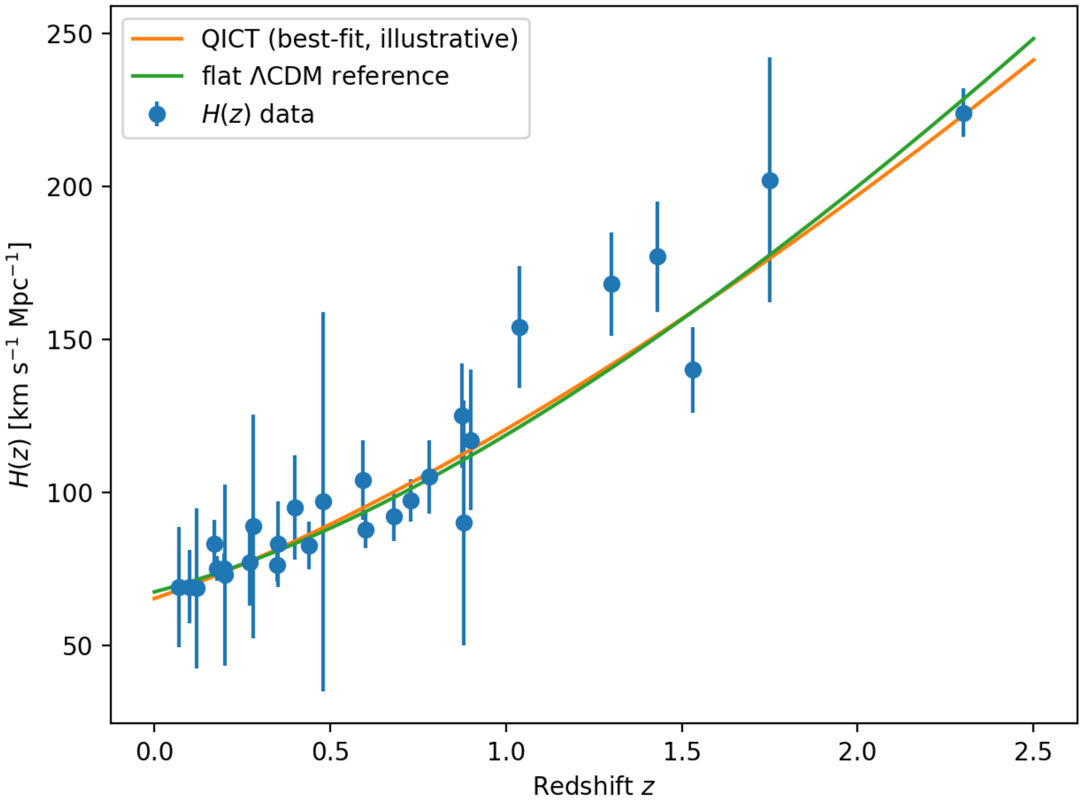

Figure 4. Minimal quantitative illustration using a public cosmic-chronometer $H(z)$ compilation: data versus an illustrative QICT closure curve (not a full likelihood analysis).

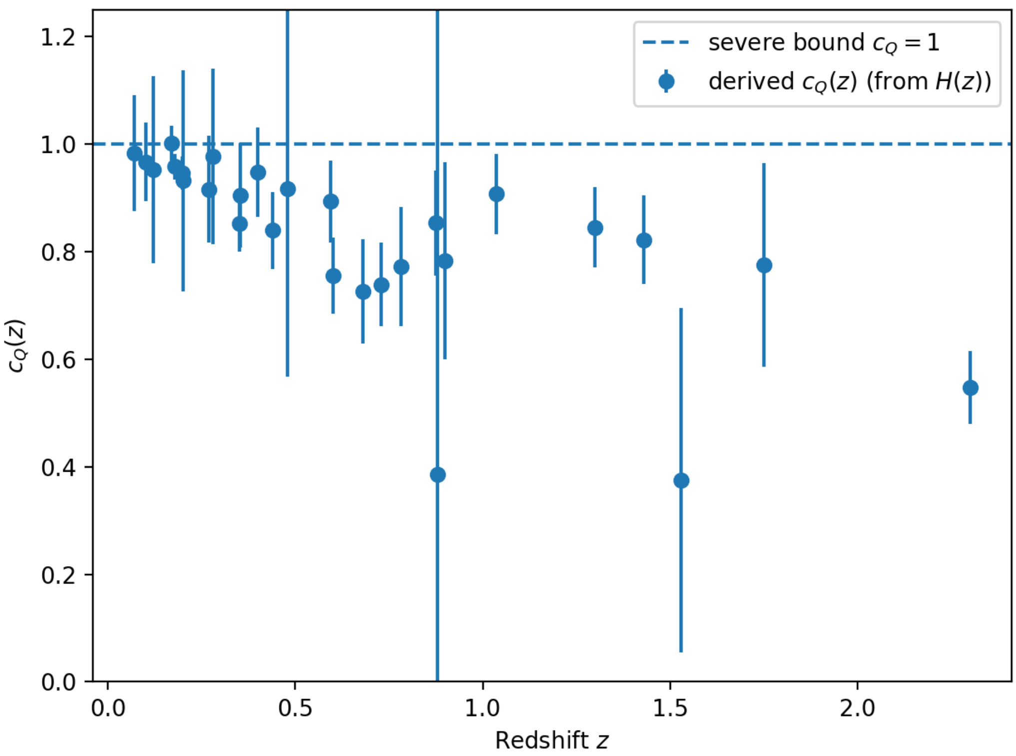

Figure 5. Derived $c_Q(z)$ from the minimal $H(z)$ illustration, displaying the strict consistency bound $c_Q(z)\le 1$ over the tested redshift range.

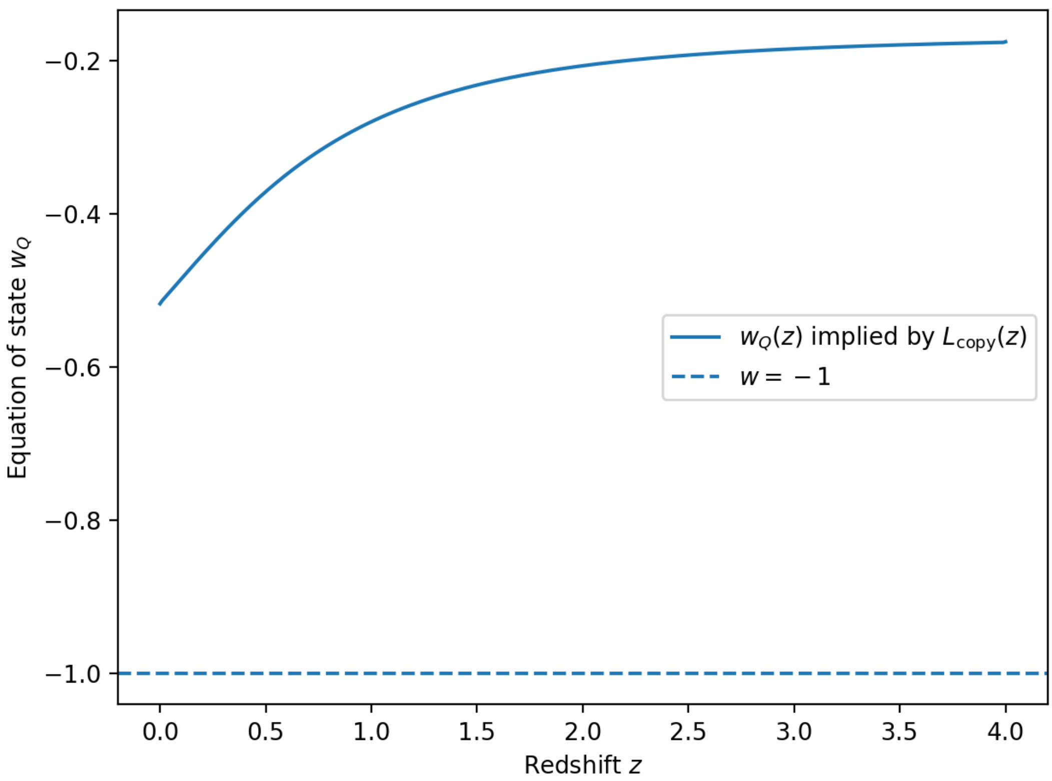

Figure 6. Illustrative (mock) evolution of the QICT equation-of-state $w_Q(z)$ implied by the copy-horizon closure.

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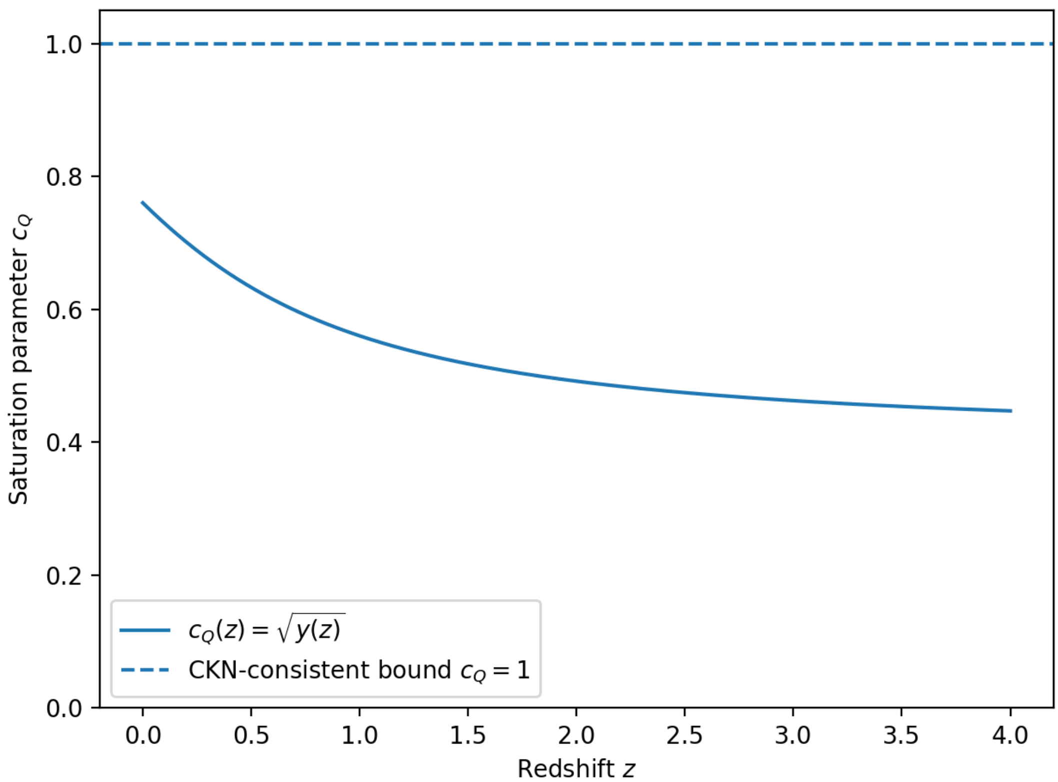

Figure 7. Illustrative (mock) evolution of the saturation parameter $c_Q(z)$ showing the falsifiable bound $c_Q(z)\le 1$ under an attractor mechanism.

Relation to Standard HDE Cutoffs (Comparator Only)

Standard holographic dark energy often adopts a future event-horizon cutoff $L_{\mathrm{HDE}} \equiv R_h$. In contrast, the present work defines L_{copy} operationally by Eq. [eq:brick1]. The event-horizon choice may be treated as a comparator model, or potentially recovered as a special case under additional assumptions on the functional dependence of $\tau_{\mathrm{copy}}(L,t)$; we do not assume such an identification in the main derivation.

Conclusions

The strict QICT copy-horizon program is characterized by (i) an operational definition of τ_{copy} and L_{copy}, (ii) a gravitational consistency bound implying L^{-2} scaling, and (iii) falsifiable saturation conditions such as $c_Q(z) \leq 1$ and multi-observable consistency relations. The accompanying Supplement and derivation package provide additional proofs, sector separation statements, and reproducible scripts.

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