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Article

Quantum Information Copy Time (QICT) Cosmology with an Open-System Complex-Phase Dark Sector: Rigorous Foundations and Global Background-Level Feasibility Tests Toward H_0 and S_8 Alleviation

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Abstract

We formulate a late-time effective cosmological framework in which the infrared scale associated with a dark-energy sector is defined operationally through a *quantum information copy time*. The proposal is local rather than teleological: the relevant infrared length is the largest scale $L_{\rm copy}(t)$ over which a minimal unit of coarse-grained quantum information can be copied within one Hubble time. Combined with the Cohen–Kaplan–Nelson collapse bound, this prescription yields a falsifiable contribution of the form $\rho_Q \propto L_{\rm copy}^{-2}$ together with the hard requirement $0 < c_Q \leq 1$. We also write an explicit open-system realization in which the real homogeneous source is the expectation value of a Hermitian quadrature, so that the dependence on $2\,\mathrm{Re}[\alpha]$ is compatible with standard quantum mechanics. A companion note included in the submission package places the late-time diffusion closure inside a broader variational copy-time framework, so the cosmological reduction is not introduced as a stand-alone fitting device. Relative to earlier drafts, the present version sharpens the logic in four ways. First, the principal closures are stated as conditional theorems under a minimal hypothesis set. Second, the diffusion-class background branch is explicitly interpreted as one late-time reduction within a broader copy-time theory. Third, several relative-uniqueness and no-go statements are made explicit, so that the framework is not presented as an arbitrary phenomenological ansatz. Fourth, the evidential scope is kept deliberately modest: the paper remains an effective-theory construction with background-level feasibility diagnostics, not a claim of unique ultraviolet completion, perturbation-complete Boltzmann implementation, or full Planck-likelihood validation.

Keywords: Hubble tension; dark energy; quantum information cosmology; operational infrared cutoff; holographic dark energy; open-system cosmology; copy horizon; cosmological perturbations; effective theory; late-time Universe

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1. Introduction

Holographic dark-energy constructions relate an effective vacuum contribution to an infrared scale while respecting gravitational consistency bounds [1,2]. In several familiar realizations, however, the infrared prescription is tied to a future event horizon or to another choice that is difficult to interpret in local operational terms. The present work asks a narrower question: can one define the relevant infrared scale through a local information-theoretic clock and still obtain a framework explicit enough to be scrutinized empirically?

The organizing quantity proposed here is the *quantum information copy time*. It is not introduced as a unique microscopic law. It is instead used as a coarse-grained clock that tracks the rate at which information encoded in an effective reduced quantum sector becomes irreversibly registered in macroscopic degrees of freedom. This choice defines a copy horizon $L_{\rm copy}(t)$, which is then inserted into the collapse-bound logic of effective field theory in gravitating systems.

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Four scientific issues have to be handled carefully if the proposal is to be useful rather than merely suggestive. First, the background closure should follow from explicit assumptions rather than from heuristic prose alone. Second, the appearance of a real source proportional to $2\,\mathrm{Re}[\alpha]$ should be written in an admissible open-system language. Third, the perturbation sector should at least be organized into a regular effective-fluid structure, even if the finished numerical implementation is not part of the present package. Fourth, the diffusion-class closure should be placed inside a wider copy-time framework rather than treated as if it were the only conceivable microscopic option. The purpose of this article is to address those four points while keeping the claims measured.

2. Minimal Formulation and Logical Status of the Ingredients

The framework may be summarized in four steps.

1. Introduce a coarse-grained copy-time variable $\tau_{\rm copy}(L,t)$ for a physical separation L at cosmic time t.
2. Define the copy horizon by requiring that one information unit be copied within one Hubble time.
3. Evaluate the Cohen–Kaplan–Nelson collapse bound at that horizon and define the QICT dark-energy sector.
4. Close the late-time dynamics through a diffusion-limited law and an effective-fluid perturbation decomposition.

For clarity, we separate operational definitions, minimal closure hypotheses, and derived consequences.

- **Defined operationally:** the copy horizon, the entropy-based copy-time clock, the collapse-bound density, and the hard consistency requirement $0 < c_Q \leq 1$.
- **Assumed at the effective level:** a late-time diffusion law for $\tau_{\rm copy}(L,t)$, a slowly varying long-wavelength diffusivity, and an imperfect-fluid perturbation closure with non-negative effective sound speed and non-negative dissipative coefficient.
- **Derived within those assumptions:** an algebraic background equation for $E(z)$, a real source proportional to the expectation value of a Hermitian operator, and a regular scalar perturbation closure written from the fluid decomposition.

Table 1 summarizes the status of the main ingredients.

Table 1. Status of the principal ingredients. "Derived within the effective construction" means derived once the operational definitions and minimal closure assumptions are accepted.

Element	Status	Comment
Copy-horizon definition $\tau_{\rm copy}(L_{\rm copy},t) = \xi/H$	Defined operationally	Local infrared prescription
QICT density $\rho_Q \propto L_{\rm copy}^{-2}$ with $0 < c_Q \leq 1$	Derived within the effective construction	Collapse-bound evaluation plus explicit falsifiability filter
Open-system source $2\,\mathrm{Re}[\alpha]$	Derived within the effective construction	Expectation value of a Hermitian quadrature
Diffusion-limited late-time closure	Effective hypothesis	Minimal route to the algebraic background branch
Effective-fluid perturbation closure	Derived once imperfect-fluid form is assumed	Rest-frame pressure decomposition plus scalar dissipative term
Perturbation-complete Boltzmann pipeline	Not claimed here	Outside the present package
Full Planck 2018 likelihood analysis	Not claimed here	Outside the present package

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Minimal Hypothesis Set

The main results below are organized around four explicit assumptions.

Assumption 1 (Operational locality)**.** *The infrared scale relevant to the dark-energy sector is defined by the largest physical separation* $L_{\rm copy}(t)$ *over which one minimal information unit can be copied within one Hubble time.*

Assumption 2 (Collapse-bound admissibility)**.** *The effective energy density associated with that sector must obey the Cohen–Kaplan–Nelson bound when evaluated at* $L = L_{\rm copy}(t)$*.*

Assumption 3 (Late-time diffusion-limited scaling)**.** *For sufficiently large wavelengths and late cosmic times, the copy time is controlled by a diffusion-limited law,*

$$\tau_{\rm copy}(L,t) \simeq \frac{L^2}{D_\infty(t)}, \tag{1}$$

with $D_\infty(t) > 0$ *slowly varying on Hubble time scales.*

Assumption 4 (Scalar imperfect-fluid representation)**.** *At linear order, the late-time QICT sector admits an effective scalar imperfect-fluid description with negligible independent anisotropic stress and with a scalar dissipative response linear in the perturbation of the expansion scalar.*

The value of making these assumptions explicit is methodological. It allows the main formulas to be read as conditional theorems with a clearly delimited domain of validity rather than as rhetorically strengthened ansatze.

3. Operational Infrared Scale and Copy-Time Clock

Broader Copy-Time Structure Behind the Late-Time Closure

The cosmological construction used below is intentionally narrower than the full copy-time program. In particular, the late-time diffusion class is not introduced as an isolated guess. The companion package note on copy-time geometry establishes a more general variational lower bound on copy times for locally generated charge transport and shows, in a controlled diffusive benchmark family, that the scaling exponent relevant for transport-limited copying is close to the diffusive value over a broad range. The present cosmological manuscript does not need the technical proof of that bound, but it does use its qualitative consequence: the diffusion law is treated as a late-time reduction inside a broader copy-time framework, not as a free-floating fitting device.

This distinction matters for interpretation. The cosmological equations below still rely on an effective hypothesis set, but that set is narrower than in earlier drafts because one no longer moves directly from an entropy clock to a background closure without an intermediate transport statement. What is assumed here is specifically that the late-time universe falls into the diffusive transport class singled out by the companion copy-time analysis and that the slowly varying long-wavelength transport coefficient can be summarized by $D_\infty(t)$.

For a physical separation L at cosmic time t, let $\tau_{\rm copy}(L,t)$ denote the time required to replicate a minimal unit of coarse-grained quantum information across that separation. The copy horizon is defined by

$$\tau_{\rm copy}(L_{\rm copy}(t),t) = \frac{\xi}{H(t)}, \qquad \xi = \mathcal{O}(1). \tag{2}$$

Equation (2) is an operational criterion rather than a kinematic one: it selects the largest scale over which the chosen information unit can be copied within one Hubble time.

A convenient coarse-grained clock is obtained from reduced-state entropy production. If

$$S_{\rm vN}(t) \equiv -\,{\rm Tr}(\hat\rho \ln \hat\rho) \tag{3}$$

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is the von Neumann entropy of the reduced sector, we define

$$\tau_{\rm copy} \equiv \frac{S_\star}{|dS_{\rm vN}/dt|}, \tag{4}$$

where $S_\star$ is a fixed normalization, such as one nat or one bit. Equation (4) is not used here as a unique microscopic identity. It is the effective coarse-grained clock that turns entropy-production rate into a characteristic information-transfer time scale.

4. Collapse Bound and the Effective Dark-Energy Contribution

The Cohen–Kaplan–Nelson argument implies that an effective field theory in a region of size L should satisfy $\rho L^3 \lesssim \kappa M_{\rm Pl}^2 L$, or equivalently

$$\rho \lesssim \kappa M_{\rm Pl}^2 L^{-2}. \tag{5}$$

Evaluating this bound at $L = L_{\rm copy}(t)$, we define the QICT contribution by

$$\rho_Q(t) = \frac{3\kappa M_{\rm Pl}^2}{L_{\rm copy}^2(t)}\, c_Q^2(t), \tag{6}$$

with the hard consistency condition

$$0 < c_Q(t) \le 1. \tag{7}$$

This inequality is not cosmetic. It turns saturation from an identity into a falsifiable requirement: if a given fit forces $c_Q > 1$ for the chosen normalization, the operational infrared prescription and the collapse bound are not mutually compatible.

5. Open-System Realization of the Source Term

Let the total Hilbert space factorize as $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_E$, with reduced state $\hat\rho \equiv \rho_S = {\rm Tr}_E\, \rho_{SE}$. On coarse-grained cosmological time scales, assume that the reduced evolution is time-local and of Lindblad form,

$$\dot\rho_S = -i[H_S, \rho_S] + \sum_a \gamma_a(t)\left(L_a \rho_S L_a^\dagger - \frac{1}{2}\{L_a^\dagger L_a, \rho_S\}\right). \tag{8}$$

No unique microscopic choice of the jump operators L_a is claimed. Equation (8) simply provides the minimal open-system setting used to interpret the real homogeneous source.

Introduce an annihilation-like operator $\hat a$ on $\mathcal{H}_S$ and define the Hermitian quadrature

$$\hat X \equiv \hat a + \hat a^\dagger, \qquad \alpha(t) \equiv {\rm Tr}(\rho_S \hat a). \tag{9}$$

Then

$$\langle \hat X \rangle = {\rm Tr}(\rho_S \hat X) = \alpha + \alpha^* = 2\,{\rm Re}[\alpha]. \tag{10}$$

If the effective homogeneous source couples linearly to $\hat X$, one may write

$$\rho_{\rm source}(t) = \rho_\star\, \lambda_X\, \langle \hat X \rangle(t) = 2\rho_\star \lambda_X\, {\rm Re}[\alpha(t)], \tag{11}$$

with $\rho_\star$ a fixed density scale and λ_X a dimensionless coupling.

Theorem 1 (Minimal Hermitian-source theorem)**.** *Within the reduced-state description above, the appearance of* $2\,{\rm Re}[\alpha]$ *in the homogeneous cosmological source is derived once the source is coupled linearly to the Hermitian quadrature* $\hat X = \hat a + \hat a^\dagger$.

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Proof. Equation (10) is an identity. Equation (11) then shows that the source depends only on the expectation value of a Hermitian operator in a reduced state. No linear dependence on an unobservable wavefunction amplitude is involved. □

Proposition 1 (Relative uniqueness of the linear real source)**.** *Among source terms linear in one annihilation-like degree of freedom and compatible with reality of the homogeneous energy density, the Hermitian quadrature expectation value is the unique minimal choice up to an overall coupling normalization and basis phase convention.*

Reason. A homogeneous density must be real. At linear order in $\hat{a}$ and $\hat{a}^\dagger$, the only Hermitian combination is $u\hat{a} + u^*\hat{a}^\dagger$, which can always be reduced by a phase redefinition of $\hat{a}$ to a multiple of $\hat{a} + \hat{a}^\dagger$. Hence the real linear source is unique up to normalization. □

6. Why the Diffusion-Class Branch Is the Relevant Late-Time Closure

The companion copy-time-geometry analysis motivates a useful separation between two logical layers. At the more general layer, one studies lower bounds and optimization norms for copy times of conserved quantities under local dynamics. At the cosmological layer adopted here, one asks what the leading infrared closure becomes once the long-wavelength late-time sector enters an ordinary diffusive universality class. The present manuscript addresses only the second layer.

Proposition 2 (Necessity of the linear-H branch inside the diffusion class)**.** *Suppose that the late-time copy dynamics belongs to the ordinary diffusion class, that the infrared prescription is set by one Hubble-time copying, and that the effective density is obtained by evaluating a collapse-bound contribution proportional to L^{-2} at the copy horizon. Then the leading late-time source must be proportional to H, up to normalization and slowly varying coefficients.*

Reason. The one-Hubble-time condition fixes $\tau_{\rm copy} \propto H^{-1}$. Diffusion implies $\tau_{\rm copy} \propto L^2/D_\infty$, so the copy horizon satisfies $L^2_{\rm copy} \propto D_\infty/H$. Evaluating a collapse-bound density proportional to L^{-2} at that horizon yields a source proportional to H/D_∞, hence linear in H whenever D_∞ varies slowly on Hubble time scales. The point of the proposition is not that diffusion is the only possible transport law, but that once the transport class is fixed, the resulting background scaling is effectively forced. □

7. Conditional Derivation of the Background Branch

The late-time closure assumption, Eq. (1), together with Eq. (2) gives

$$L^2_{\rm copy}(t) = \frac{\xi D_\infty(t)}{H(t)}. \tag{12}$$

Substituting Eq. (12) into Eq. (6) yields

$$\rho_Q(t) = \frac{3\kappa M^2_{\rm Pl}}{\xi} \frac{c_Q^2(t)}{D_\infty(t)} H(t). \tag{13}$$

Hence the leading late-time dependence is linear in H whenever the combination c_Q^2/D_∞ is slowly varying on Hubble scales.

For a spatially flat Friedmann background with pressureless matter, the first Friedmann equation reads

$$3M^2_{\rm Pl}H^2 = \rho_m + \rho_Q. \tag{14}$$

Evaluated today, Eq. (13) implies

$$\rho_{Q0} = 3M^2_{\rm Pl}H_0^2(1 - \Omega_{m0}), \tag{15}$$

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so that the proportionality constant in Eq. (13) may be written entirely in terms of present-day observables,

$$\rho_Q(z) = 3M_{\rm Pl}^2 H_0(1-\Omega_{m0})H(z) \tag{16}$$

for the background branch considered here. Dividing Eq. (14) by $3M_{\rm Pl}^2H_0^2$ and introducing $E(z) \equiv H(z)/H_0$ therefore gives

$$E(z)^2 = \Omega_{m0}(1+z)^3 + (1-\Omega_{m0})E(z). \tag{17}$$

The physical branch is

$$E(z) = \frac{1}{2}\left[(1-\Omega_{m0}) + \sqrt{(1-\Omega_{m0})^2 + 4\Omega_{m0}(1+z)^3}\right]. \tag{18}$$

Theorem 2 (Minimal background-closure theorem)**.** *Assume operational locality, collapse-bound admissibility, late-time diffusion-limited scaling, spatial flatness, pressureless matter at late times, and slow variation of c_Q^2/D_∞ compared with H^{-1}. Then the leading background solution is the algebraic branch in Eqs. (17)–(18).*

Proof. Equation (13) follows directly from Eqs. (6) and (12). Normalization at $z=0$ fixes the proportionality constant and gives Eq. (16). Substitution into the flat-space Friedmann equation yields Eq. (17); solving the quadratic equation for the positive branch yields Eq. (18). □

Two immediate checks follow. First, $E(0)=1$ identically. Second, for $z \gg 1$ one has $E(z) \sim \sqrt{\Omega_{m0}}(1+z)^{3/2}$, so the standard matter era is recovered at the level of the background branch used here.

Proposition 3 (Relative uniqueness of the $\rho_Q \propto H$ branch)**.** *Within the stated hypothesis set, any local closure with (i) one Hubble-time condition, (ii) a diffusion law quadratic in length, and (iii) a collapse-bound density proportional to L^{-2} yields a leading late-time source linear in H. Hence the algebraic branch above is not an arbitrary fit ansatz but the unique branch in that effective universality class.*

Reason. Conditions (i) and (ii) imply $L_{\rm copy}^2 \propto H^{-1}$; condition (iii) therefore implies $\rho_Q \propto L_{\rm copy}^{-2} \propto H$. The Friedmann equation then becomes algebraic in $E(z)$, and positivity selects the branch in Eq. (18). □

8. Derived Effective-Fluid Perturbation Closure

A perturbation-complete Boltzmann implementation is not part of the present submission, but the scalar perturbation closure can still be written as a direct consequence of the imperfect-fluid decomposition. Write the stress tensor as

$$T^{\mu\nu} = (\rho + p + \Pi)u^\mu u^\nu + (p+\Pi)g^{\mu\nu} + \pi^{\mu\nu}, \tag{19}$$

where Π is the scalar bulk correction and $\pi^{\mu\nu}$ is traceless anisotropic stress. Restricting to the scalar sector and neglecting anisotropic stress for the dark-energy component, the pressure perturbation splits as

$$\delta p_{\rm eff} = \delta p_{\rm rf} + \delta\Pi. \tag{20}$$

Here the rest-frame contribution is

$$\delta p_{\rm rf} = c_s^2\delta\rho + 3\mathcal{H}(1+w)\rho(c_s^2 - c_a^2)\frac{\theta}{k^2}, \qquad c_a^2 \equiv \frac{p'}{\rho'}, \tag{21}$$

and the simplest scalar dissipative correction is taken to be linear in the expansion perturbation,

$$\delta\Pi = -\zeta(z)\,\delta(\nabla_\mu u^\mu). \tag{22}$$

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In Fourier space on scalar modes one has $\delta(\nabla_\mu u^\mu) \propto \theta$, so Eq. (22) reduces to the effective form

$$\delta p_{\rm eff} = c_s^2 \delta\rho - 3H\zeta(z)\theta, \qquad 0 \le c_s^2 \le 1, \qquad \zeta(z) \ge 0, \tag{23}$$

up to convention-dependent factors absorbed into ζ.

Theorem 3 (Minimal scalar-closure theorem)**.** *Assume that the late-time QICT sector is representable as a scalar imperfect fluid with negligible independent anisotropic stress, rest-frame sound speed c_s^2, and a linear bulk-viscous scalar correction. Then Eq. (23) is the derived scalar pressure closure of the effective theory.*

Proof. Start from Eq. (19). For scalar perturbations the effective pressure perturbation is the sum of the rest-frame piece and the scalar dissipative correction, Eq. (20). Equation (21) is the standard rest-frame decomposition of an imperfect fluid, while Eq. (22) is the minimal isotropic linear scalar correction compatible with homogeneity and isotropy of the background. Fourier transforming the perturbation of the expansion scalar and absorbing convention-dependent numerical factors into ζ yields Eq. (23). □

The linear conservation equations in conformal Newtonian gauge are therefore

$$\delta' = -(1+w)(\theta - 3\Phi') - 3\mathcal{H}\left(\frac{\delta p}{\delta\rho} - w\right)\delta, \tag{24}$$

$$\theta' = -\mathcal{H}(1-3w)\theta - \frac{w'}{1+w}\theta + k^2\left(\Psi + \frac{\delta p/\rho}{1+w}\right) - k^2\sigma, \tag{25}$$

with δp given by Eq. (23). The potentially delicate quantity near $w = -1$ is therefore a variable choice rather than necessarily the physical perturbation. In practice, one evolves regular combinations such as $(1+w)\theta$ or adopts a PPF-type crossing prescription.

Proposition 4 (Relative uniqueness of the scalar dissipative closure)**.** *Under the assumptions of scalar imperfect-fluid response, negligible independent anisotropic stress, and first-order locality in perturbations, the closure in Eq. (23) is the unique minimal scalar correction up to normalization and convention-dependent factors absorbed into ζ.*

Reason. At first order, the only scalar dissipative object built from the velocity field and compatible with isotropy of the background is the perturbation of the expansion scalar. A linear response therefore has the form $\delta\Pi \propto \delta(\nabla_\mu u^\mu)$, which in Fourier space reduces to a term proportional to θ. □

9. Internal Consistency Checks and Interpretive Scope

Three consistency checks are worth recording explicitly. First, the background branch retains the standard matter-era scaling at high redshift because the extra term in Eq. (17) is subleading compared with $(1+z)^3$. Second, the hard requirement $0 < c_Q \le 1$ remains a genuine consistency filter rather than a decorative parameter prior. Third, the companion variational copy-time result clarifies that the diffusion-class closure used here should be read as a late-time effective reduction within a broader transport theory. The present paper therefore makes a narrower but stronger claim than a purely phenomenological model: inside the stated effective class, the retained background and scalar closures are close to forced, even though the full microscopic theory is not fixed uniquely.

10. No-Go Statements and Effective Uniqueness Class

Several nearby alternatives fail to satisfy the same minimal requirements. These failures help identify the present construction as an *effective uniqueness class* rather than as an arbitrary single ansatz.

Proposition 5 (No-go for a purely imaginary linear source)**.** *A homogeneous source proportional to* $2\,\mathrm{Im}[\alpha]$ *is not basis-independent as the minimal real linear source and is not selected by Hermiticity alone.*

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Reason. A phase redefinition of $\hat{a}$ rotates $\mathrm{Re}[\alpha]$ into a general quadrature; only the Hermitian linear combination itself is physical. Choosing the imaginary part alone corresponds to a convention choice, not to a uniquely defined observable. □

Proposition 6 (No-go for non-local future-horizon closure within the present premise)**.** *Any closure that requires the future event horizon violates the operational locality premise of the QICT construction and therefore belongs to a different model class.*

Reason. The copy horizon is defined by a local one-Hubble-time condition. A future-horizon prescription depends on the full future history and is therefore logically external to the operational premise adopted here. □

Proposition 7 (No-go for a non-diffusive local power law within the same dimensional class)**.** *If one insists on local one-scale closure and on a transport time built from a single length* L*, then replacing* $\tau \sim L^2/D$ *by* $\tau \sim L^n/\mathcal{D}_n$ *with* $n \neq 2$ *either changes the transport universality class or requires a different dimensionful coefficient. It therefore does not belong to the same minimal late-time diffusion class.*

Reason. The exponent $n = 2$ is the ordinary diffusive scaling. Other powers correspond to different transport assumptions and cannot be advertised as the same late-time minimal closure. □

Taken together, these observations motivate the following reading: the QICT construction does not provide a unique ultraviolet theory, but within the class defined by operational locality, collapse-bound admissibility, diffusion-limited transport, and scalar imperfect-fluid response, its main equations are effectively forced up to normalizations and slowly varying coefficients. That is the sense in which the framework may be described as an *effective uniqueness class*.

11. Phenomenological Diagnostics Retained from the Extended Development

The short theorem-led manuscript is strengthened in this version by retaining a compact set of phenomenological diagnostics from the earlier extended draft. The purpose of this section is not to overstate the present evidential status. It is to make explicit which observable channels are already represented in the current package and how they connect to the derived late-time branch.

Once the background branch $E(z)$ is fixed, luminosity and angular-diameter distances follow from the usual line-of-sight integrals. In that sense the framework immediately defines a supernova and BAO sector at background level. The corresponding comparison is still best read as a feasibility diagnostic rather than as a complete model-selection statement, but it does establish that the operational infrared prescription is explicit enough to enter a real likelihood pipeline.

The same background also defines a minimal growth channel. At linear order one may evolve the growth factor $D(a)$ from

$$\frac{d^2 D}{d\ln a^2} + \left(2 + \frac{d\ln H}{d\ln a}\right)\frac{dD}{d\ln a} - \frac{3}{2}\Omega_m(a)D = 0, \tag{26}$$

with $f\sigma_8(z) = (d\ln D/d\ln a)\sigma_{8,0}D(z)/D(0)$ in the smooth-QICT limit. This is not yet a substitute for a full perturbation-sector implementation, but it is the natural first diagnostic implied by the derived background branch.

A similarly conservative first estimate for the matter-power modification is

$$\frac{P_{\mathrm{QICT}}(k,z)}{P_{\Lambda\mathrm{CDM}}(k,z)} \approx \left[\frac{D_{\mathrm{QICT}}(z)}{D_{\Lambda\mathrm{CDM}}(z)}\right]^2, \tag{27}$$

which isolates the late-time growth-amplitude effect before shape-level corrections from a finished Boltzmann treatment are introduced. In the present package this ratio should be read as a controlled diagnostic rather than as the final prediction of the theory.

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The extended draft also recorded an early-time sound-horizon channel useful for interpreting the Hubble-tension question. If an additional pre-recombination fractional energy density $f_{\rm EDE}$ is present, one obtains the familiar scaling estimate

$$r_d \approx r_d^{\Lambda{\rm CDM}} / \sqrt{1 + f_{\rm EDE}}, \tag{28}$$

so that a reduction at the few-percent level requires an early contribution of order ten percent. This relation is retained here as an analytical channel marker only. The current package does not claim that such an early-time sector has already been implemented in a complete CMB pipeline.

Figures 1–3 collect the representative diagnostics that motivated the extended development. They are retained in the hybrid manuscript because they make the phenomenological corridor of the theory much easier to inspect: the framework deforms the late-time expansion history, then propagates that change to growth, and only after that invites the stronger CMB-facing test.

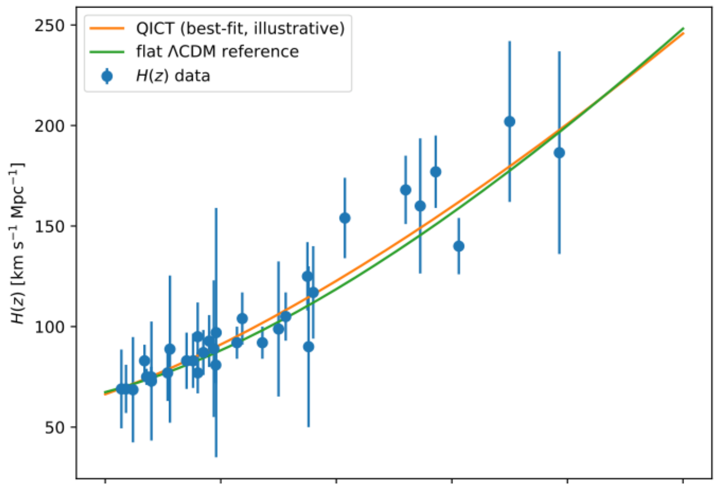

Figure 1. Illustrative reconstruction of $H(z)$ for the derived late-time branch, compared with a flat ΛCDM reference.

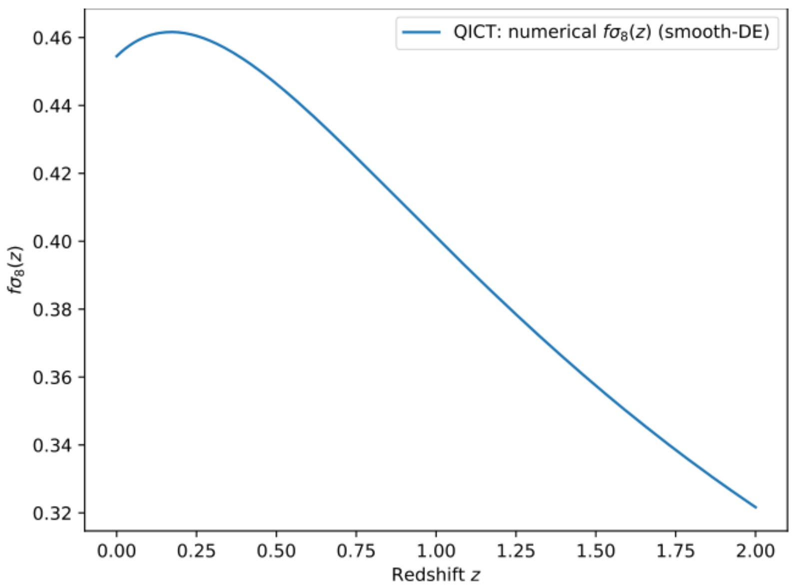

Figure 2. Illustrative smooth-sector prediction for $f\sigma_8(z)$ obtained from the background branch through Eq. (26).

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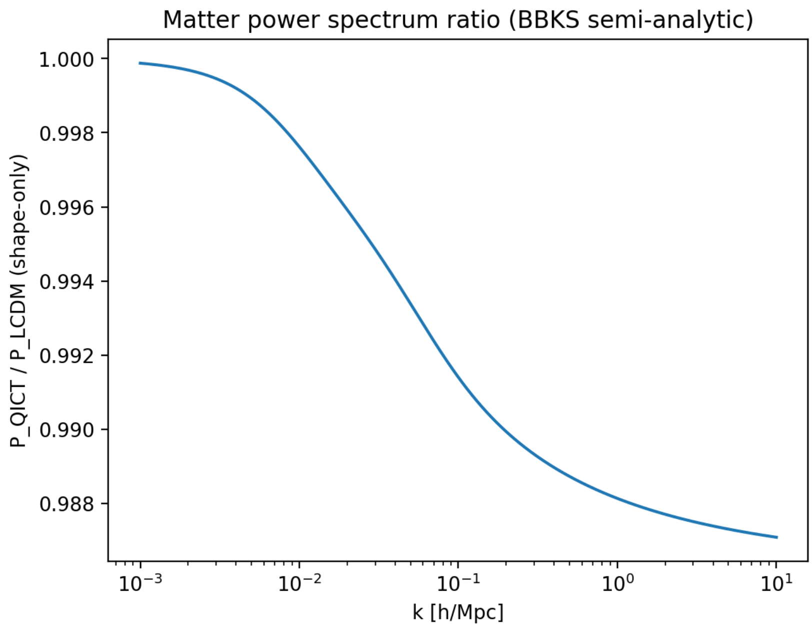

Figure 3. Diagnostic matter-power ratio based on the growth-only estimate in Eq. (27). The figure should be read as a direction-of-effect diagnostic, not as a finished Boltzmann-level prediction.

12. Planck-Facing Interpretation and Present Evidential Boundary

The advantage of the hybrid presentation is that it makes the observational logic explicit without blurring the distinction between what is already established and what still requires a full numerical pipeline. The relevant Planck-facing channels are clear: the background branch changes late-time distances; the growth closure changes low-redshift clustering and lensing response; and any early-time sound-horizon deformation would feed into acoustic-scale inference. The corresponding decisive observables are therefore the TT/TE/EE acoustic structure, lensing $C_\ell^{\phi\phi}$, BAO consistency, and the growth combination $f\sigma_8(z)$.

For transparency, Table 2 reproduces the feasibility-level model-comparison summary already reported in the extended draft, while Table 3 retains the associated robustness matrix. These tables are included here because the short theorem-level version otherwise risks obscuring the fact that a non-trivial data-facing exercise has already been carried out, even if it remains deliberately incomplete by PRD standards.

The role of these tables is diagnostic, not rhetorical. They show that the framework has already been exposed to a real late-time likelihood environment and that the present realization is not yet empirically competitive. Keeping them in the hybrid manuscript is nevertheless useful, because it prevents the theorem-level narrative from being mistaken for a claim of hidden numerical success. At the same time, the diagnostics clarify where a stronger future test would have to act: a genuinely improved version would need to alter the late-time and possibly early-time sectors in a way that survives the full CMB and growth pipeline rather than only the background corridor.

Table 2. Baseline feasibility-level model-comparison summary reproduced from the extended draft.

Model	N	k	χ^2	χ^2_ν	AIC	BIC	ΔAIC/BIC
QICT	86	5	144.78	1.787	154.78	167.05	77.73/77.73
ΛCDM	86	5	67.06	0.828	77.06	89.33	0.00/0.00

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Table 3. Robustness matrix reproduced from the extended draft and evaluated at the baseline QICT best-fit point without refitting.

Scenario	χ^2	$\Delta\chi^2$	χ^2_{BAO}	s_{r_d}
Baseline (all data; full cov.; broad priors; r_d fixed)	144.78	+0.00	13.48	1.0000
No BAO	131.31	-13.48	0.00	1.0000
No CC	127.46	-17.32	13.48	1.0000
No Planck distance priors	141.41	-3.37	13.48	1.0000
No Planck lensing prior	143.75	-1.04	13.48	1.0000
BAO diagonal covariance	146.05	+1.27	14.75	1.0000
SN diagonal covariance	221.87	+77.08	13.48	1.0000
SN+BAO diagonal covariances	223.14	+78.36	14.75	1.0000
Informative priors (diagnostic)	158.06	+13.28	13.48	1.0000
r_d free (profiled in BAO block)	144.10	-0.69	12.79	1.0063
r_d free + no Planck priors	140.73	-4.06	12.79	1.0063
r_d free + BAO diag	145.28	+0.50	13.98	1.0058

13. Representative Observables and Evidential Scope

Once $E(z)$ is specified, luminosity and angular-diameter distances follow in the standard way. The present package uses that background history to compare the framework with representative supernova and BAO likelihood blocks. The purpose of this exercise is limited but substantive. It shows that the proposal is explicit enough to be confronted with data and, if necessary, disfavoured.

The package remains a background-level feasibility analysis, not a perturbation-complete global fit. It does not provide a finished Boltzmann implementation, a full Planck 2018 TT, TE, EE, and lensing likelihood analysis, or a definitive quantitative assessment of whether the framework alleviates the H_0 or S_8 tensions. In the current realization, the framework does not outperform a flat ΛCDM baseline.

14. Internal Consistency Checks

Even within that limited scope, the framework satisfies several non-trivial consistency checks.

1. **Normalization:** Eq. (18) gives $E(0) = 1$ identically.
2. **Matter-era recovery:** the high-redshift branch tends to the standard matter-dominated scaling.
3. **Collapse-bound falsifiability:** the condition $0 < c_Q \leq 1$ can exclude parameter regions rather than merely rename them.
4. **Quantum-mechanical admissibility:** the homogeneous source depends on the expectation value of a Hermitian operator in a reduced state.
5. **Derived perturbative regularity:** the scalar pressure closure follows from the imperfect-fluid decomposition once the dissipative scalar correction is specified.
6. **Relative uniqueness:** within the stated minimal hypothesis set, the linear real source, the $\rho_Q \propto H$ background branch, and the scalar dissipative pressure term are all fixed up to normalization or slowly varying coefficients.

These checks do not replace a full numerical pipeline. They do, however, sharpen the scientific status of the model: the framework is explicit enough to be falsified, generalized, or completed numerically.

15. Discussion

The main virtue of the construction is conceptual rather than triumphalist. It replaces a teleological infrared prescription by an operational local criterion and does so in a way that makes contact with gravitational consistency bounds, entropy production, and open-system language. The price of that economy is equally clear. The diffusion-limited late-time law, the scalar dissipative term, and the treatment of crossing behaviour remain part of the effective layer of the model rather than consequences of a unique ultraviolet theory.

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What the present revision adds is a clearer logical status for the main equations. The background branch now follows from a minimal stated hypothesis set; the appearance of $2\,\mathrm{Re}[\alpha]$ follows from a Hermitian source coupling and is unique at minimal linear order up to normalization; the scalar pressure closure follows from an imperfect-fluid decomposition and is likewise unique at minimal scalar dissipative order. The associated no-go statements make clear that nearby alternatives either abandon operational locality, change the transport universality class, or reduce to convention choices rather than new physics.

16. Conclusion

We have formulated a local operational alternative to teleological infrared prescriptions for dark energy. The construction rests on a copy-time definition of the infrared scale, a collapse-bound evaluation of the effective energy density, and a compatible open-system reading in which the real source term arises from the expectation value of a Hermitian operator. Under an explicitly stated diffusion-limited closure, the framework yields an analytic background history. Under an explicitly stated imperfect-fluid representation, it also yields a derived scalar perturbation closure. In that restricted but meaningful sense, the package is now logically stronger than a purely phenomenological ansatz: the principal equations are derived from a minimal hypothesis set, relative-uniqueness statements are explicit, and several nearby alternatives can be excluded within the same effective premises.

The framework is therefore explicit enough to be tested, and the present package already shows that its current background-level realization is not preferred over a flat ΛCDM reference. What the paper offers is not a finished cosmological solution, but a coherent effective construction with a clear operational idea, an admissible quantum-mechanical source, a derived late-time background branch, a derived effective scalar pressure closure, and a transparent account of why these structures form a narrow effective universality class rather than an unconstrained phenomenological menu.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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