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Why the Observable Universe Is Not Fundamental

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Abstract

The observable universe has always remained below its own gravitational radius—yet it is not the interior of a black hole. This apparent paradox, derivable from the Friedmann equations, suggests that three-dimensional space is not the fundamental level of physical description. In this work: (1) we derive the global gravitational constraint $R_p \lesssim R_g$ valid in every cosmic epoch; (2) we prove with a causal no-go theorem that this constraint does *not* imply a black hole-type geometry; (3) we show that, within standard physics, the resolution that survives the exclusion of alternatives is holographic: fundamental information resides on a two-dimensional boundary, while the interior volume is an emergent reconstruction. The ingredients of this argument—Friedmann cosmology, covariant entropy bounds, holographic counting—are individually well established. What has been missing is their systematic combination into a closed logical chain. If this chain were trivial, holographic cosmology would already be the dominant paradigm and inflation would be recognized as optional. It is not, which suggests the synthesis itself is the contribution. The framework dissolves what we call the "spacetime island" problem: in standard physics, coordinates are treated as primitives disconnected from the informational language of quantum theory and statistical mechanics. Holographic emergence reconnects them. Giving up one or two "fundamental" dimensions is a gain in parsimony and unification, not a loss. Observable consequences follow. The Gaussianity of the CMB emerges from the central limit theorem applied to boundary degrees of freedom. Primordial gravitational waves are expected to be strongly suppressed ($r < 10^{-3}$); a robust detection at $r > 10^{-2}$ would falsify the minimal framework. Recent observations—the absence of predicted dark matter subhalos in high-resolution lensing, the anomalous pressure in cluster mergers—provide independent hints that the standard picture has cracks where this framework offers natural explanations.

Keywords: holographic principle; emergent spacetime; cosmological horizons; covariant entropy bound; foundations of cosmology; central limit theorem; primordial perturbations

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Positioning of This Work

The individual elements discussed in this paper—the gravitational bound $R_p \lesssim R_g$, the holographic principle, the causal structure of FRW spacetimes—are well established in the literature. The near-saturation of gravitational bounds in cosmology was noted by Padmanabhan [1]; holographic ideas trace back to 't Hooft, Susskind, and Bousso [2–4]; the thermodynamic interpretation of gravity was developed by Jacobson [5] and Verlinde [6].

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What is new here is the systematic combination of these elements into a single logical chain that leads to specific, falsifiable conclusions:

1. **Systematic tracking**: we show that the constraint $R_p/R_g = (R_H/R_p)^2$ holds across *all* cosmic epochs (radiation, matter, Λ), not as a coincidence but as an algebraic identity.
2. **Explicit exclusion of alternatives**: we formalize in invariant language why $R_p \sim R_g$ does not authorize the "black hole interior" interpretation, and why volumetric, modified-gravity, and coincidence-based alternatives fail.
3. **From bound to observable**: we introduce a coarse-graining prescription (via $N_{\rm eff}$ and a physically-derived correlation scale $L_{\rm corr}$) that connects microstatistical bounds to observable amplitudes without invoking inflation as a logical necessity.
4. **Foundation for the entropic programme**: This paper provides the logical foundation for the entropic hysteresis framework developed in the companion work [7], showing *why* holographic description is necessary before that paper shows *how* it generates specific dynamics.

Closing this logical chain is the contribution of this paper. If it were obvious, the holographic-entropic interpretation of cosmology would already be the dominant paradigm and inflation would be widely recognized as optional rather than necessary. The fact that this is not the case suggests that the chain, though built from known ingredients, has not been previously written down in this form.

Why this reframing matters: unification vs isolation. In classical and relativistic physics, spacetime is an island. Its quantities—coordinates, metric, curvature—are treated as *primitive givens*: they exist with no microstructure, no informational content, no connection to the language of the rest of physics (statistical mechanics, quantum theory, information theory). A theory of everything that unifies gravity with quantum physics cannot leave this island untouched.

The entropic-holographic framework dissolves the island. It describes spacetime in the same language as the rest of physics: degrees of freedom, entropy, bounds, correlations. The coordinates are no longer primitive; they emerge from something that *has* structure, *is* definable, *connects* to everything else.

Giving up one or two "fundamental" dimensions is not a loss. It is a gain: compactness, parsimony, unification. The alternative to this framework is not "staying with Einstein." It is making the standard picture *more* complex and *less* parsimonious to explain the same facts—or modifying General Relativity in ways not yet explored.

Scope and Limits of This Work

Before proceeding, we state explicitly what this paper does and does not claim.

This work does not claim to:

- Derive quantum gravity from first principles.
- Provide a complete theory of the boundary degrees of freedom.
- Replace all of inflationary cosmology with a finished alternative.
- Solve all open problems in cosmology.

It claims only to show that:

- Within the minimal assumptions adopted here (GR + covariant entropy bounds + standard causal structure), the holographic description is the option that survives the exclusion of volumetric, modified-gravity, coincidence-based, and coordinate-artifact alternatives.

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- Standard cosmology already contains this necessity, hidden in plain sight.
- The framework makes falsifiable predictions that future experiments will test.

This "anti-overclaim" framing is essential: the paper presents a *necessity argument*, not a complete theory. The companion works [7,8] develop the dynamical mechanism and propose a laboratory test; this paper establishes why such a mechanism is required.[1]

Clarification (scope and novelty). While each ingredient is standard, the novelty here is not a new bound but a new *logical dependence*: the near-saturation of the FRW gravitational constraint and the causal no-go jointly force a boundary description as the minimal consistent accounting of degrees of freedom, rather than an optional interpretive layer.

Related Work and Acknowledgement of Precedents

It is important to be explicit about what is, and is not, original in the present analysis. The author does not claim novelty for any of the following individual results:

- The near-saturation of the gravitational scale by the observable scale in flat FRW. The relevant identity $R_p \lesssim R_g$ can be extracted from the standard Friedmann equations, and equivalent statements appear in Padmanabhan's work on horizon thermodynamics [1,10] and in the thermodynamic formulation of Friedmann dynamics by Cai and Kim [11].
- The causal incompatibility between FRW expansion and the interior of a Schwarzschild-type black hole. The question was raised explicitly by Pathria [12] and analyzed via Penrose diagrams by Stuckey [13], both reaching the same negative conclusion at the structural level.
- The application of the holographic principle to cosmology. The general idea was developed by 't Hooft [2] and Susskind [3]; the program of holographic cosmology as a research direction was proposed by Banks and Fischler [14]; the covariant entropy bound that makes the area scaling rigorous in dynamical spacetimes is due to Bousso [4].
- The thermodynamic interpretation of Einstein's equations and the entropic origin of gravity, developed respectively by Jacobson [5] and Verlinde [6].
- The entanglement–geometry correspondence, in which interior geometry is reconstructed from boundary correlations, established by Ryu and Takayanagi [15] and articulated as "spacetime from entanglement" by Van Raamsdonk [16].

The following table summarizes what is established in the cited works and what is new here.

[1] A unified theoretical framework connecting the holographic boundary to particle physics is also under development in [9].

Table 1. What this paper claims, and what it does not claim, relative to existing literature.

Established in prior work	New element of the present argument
$R_p \lesssim R_g$ in flat FRW, derivable from Friedmann [1,10,11]	The identity $R_p/R_g = (R_H/R_p)^2$ tracked explicitly across all cosmic epochs (radiation, matter, Λ) as an algebraic statement, not a coincidence (Theorem 1)
"Universe as a black hole" interpretation excluded on causal grounds [12,13]	Formalized as Theorem 2 with explicit conditions (global hyperbolicity, future-complete geodesics, $H > 0$) and citations to Penrose–Hawking–Ellis [17,18]
Holographic principle in cosmology [2–4,14]	Derived as the *minimal consistent option* from Friedmann + Bousso bound + causal no-go, with explicit exclusion of the volumetric, modified-gravity, and coincidence alternatives (Sec. 4.3)
Bekenstein–Hawking–Bousso area scaling [4,19, 20]	Connected to a coarse-graining prescription (N_{eff}, L_{corr}) that maps microstatistical counting to observable CMB amplitude, without invoking inflation as a logical necessity
Geometry from entanglement [15,16]	Used as the reconstruction mechanism that closes the chain, with the entropic-time parametrization τ_S as the natural evolution variable (Chapter 5)

What is claimed here is the *closure of the logical chain* that uses these ingredients to derive the holographic description as the minimal consistent option within the assumptions adopted. Each ingredient is standard; the dependence between them—that the near-saturation of the FRW gravitational constraint plus the causal no-go jointly force a boundary description as the minimal consistent accounting of degrees of freedom—is, to the author's knowledge, not previously articulated in this form. The conclusion "the observable universe is not fundamental" is not assumed at the outset and is not present in the cited works; it is the endpoint of the logical chain that this paper aims to make explicit.

1. Chapter 1 — Prologue

The naive question (that is not naive), and why nobody wants to hear it anymore

There is a standard question in cosmology that resurfaces in every general-relativity course sooner or later: if the observable universe contains an amount of mass-energy of order 10^{53} kg (consistent with the critical density and the Hubble radius from Planck 2018 cosmology [21]) in a region comparable to its own gravitational radius, in what sense is it not a black hole?

The standard reply—"because space is expanding"—is correct as far as it goes, but it does not close the question. The numerical proximity between R_{obs} and R_g is structural: it persists across every cosmic epoch, and a near-coincidence that survives three different dynamical regimes is worth taking seriously rather than dismissed as a coordinate artifact. *Why* does the Einstein–Friedmann solution permit an open future when, by naive accounting, the system looks "more compact" than a black hole of equal mass?

This paper takes that question seriously. It does not dismiss it as confusion about coordinates. It formalizes it, tracks it through all cosmic epochs, and shows that the answer changes what we mean by "space," "time," and "fundamental."

Why this matters. If the framework developed here is correct, it has consequences on three open questions in standard cosmology. The directionality of time no longer requires asymmetric initial conditions: it follows from the accumulation of entropy on the boundary. Large-scale isotropy no longer requires fine-tuning: it follows from boundary statistics combined with the central limit theorem. And the notion of space shifts: not the fundamental physical substrate, but an effective reconstruction from holographic data. These are not three independent results; they are three consequences of one structural choice.

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Operational definitions. To avoid ambiguity: we use "*fundamental*" in a technical sense—a description is fundamental if expressed in terms of degrees of freedom that do not require reconstruction from a deeper level. We call the cosmological bulk "*emergent*" because, in the framework we develop, it is an effective description obtained via coarse-graining from boundary (screen) data.

The question can be sharpened. If the Universe originates from an enormously dense phase, then there exists a primordial epoch when the mass-energy now in the observable universe was concentrated in a region smaller than $R_g = 2GM/c^2$. Put with the brutality of freshman calculations: "for a given M, if $R < R_g$, shouldn't we be *inside* a horizon? And if so, how did we manage to *expand* instead of collapsing to a singularity?"

Figure 1. Comparison between $R_{\rm obs}(t)$ (here identified with the particle horizon R_p) and the gravitational radius R_g of the mass-energy contained within $R_{\rm obs}$. The near-saturation $R_{\rm obs} \sim R_g$ is structural and is the empirical motivation for the rest of the manuscript; it does not imply that the Universe is the interior of a black hole, which is excluded on causal grounds in Chapter 3.

Reading note. The figure serves only to fix the scales; the constraint is rigorously derived in Chapter 2.

General Relativity is not a set of metaphors: it is a causal theory. Inside a black hole-type horizon, the orientation of future geodesics and the structure of light cones impose a destiny: the future is "toward $r = 0$". So the question becomes sharper: if the Universe does *not* evolve toward a singularity and, indeed, appears to be in accelerated expansion, what geometric object are we really describing when we calculate R_g from the mass-energy of the observable volume?

1.1. The Comparison of Scales: Coincidence or Structure?

The gravitational radius $R_g = 2GM/c^2$ is the scale at which gravity bends causality and geometry. The "mass of the Universe" is a problematic concept, but the "mass-energy contained in the observable universe" is operationally defined: the observable is what is causally connected to us.

The surprising fact is that $R_{\rm obs} \sim R_g$ is not a coincidence of the current epoch. It persists through different epochs—radiation, matter, dark energy. A coincidence that persists for 13.8 billion years through three different dynamical regimes is not chance: it is a structural constraint.

This article derives that constraint (Chapter 2) and explores its consequences.

1.2. Standard Objections (and Why They Do Not Close the Problem)

To avoid interpretive shortcuts, we adopt from the outset some *operational criteria* ("guardrails") that we will use recurrently.

1. **Dependence on assumptions:** if a paradox disappears by changing a single "boundary" hypothesis, then that hypothesis must be made explicit and discussed (not hidden).
2. **Causality first:** every interpretation must be compatible with causal structure (horizons, conformal diagrams, null expansions). Numerical comparisons alone are not enough.
3. **Information bounds:** if the theory imposes a covariant limit on accessible information, it cannot be treated as an aesthetic detail.
4. **Temporal persistence:** an effect valid only "today" may be a coincidence; an identity valid in every epoch indicates structure.
5. **Translatability:** a sentence that cannot be translated into equations or a geometric (causal) criterion remains narrative; narrative is useful, but does not replace physics.

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This article tries to hold both together: *narrative and proof*. The first makes the problem readable, the second makes the proposal verifiable (or falsifiable).

1.3. The Most Common Deception: "Inside a Black Hole" as a Shortcut

A common reaction to the question of Chapter 1 is the shortcut: "so we live inside a black hole". It is seductive because it seems to close the circle—if the observable universe is smaller than its gravitational radius, then it is "inside" a black hole—but the shortcut fails already at the causal level.

The interior of a black hole, in the geometric sense of classical General Relativity, is a precise object. It is defined simultaneously on three levels: causally, by the presence of trapped surfaces (both radial null expansions negative); dynamically, by future-directed timelike geodesics that terminate at a singularity in finite proper time; topologically, by the orientation of the future light cone toward $r = 0$. These three conditions hold together. The shorthand "we are inside a black hole" implies all three; FRW satisfies none of them.

The observed Universe, on the other hand, exhibits an open future, an expansion, and a cosmic history that does not run toward a future singularity as an inevitable destiny (at least in the standard post-big bang description). The Universe does not behave like the interior of a classical black hole.

The first methodological point of this work emerges already here: dimensional comparability of two radii is not sufficient to identify two geometries. What determines geometric identity is the causal structure—the orientation of the light cones and the global behaviour of timelike geodesics.

The shortcut "we are inside a black hole" is not a solution but a problem disguised as one. The standard reply "FRW is not a black-hole interior" is correct on the causal level but incomplete as an explanation: it accounts for what FRW *is not*, but not for why R_{obs} stays close to R_g across radiation domination, matter domination, and the Λ-dominated epoch—three regimes with very different dynamics. A near-coincidence that survives three regimes over 13.8 billion years is not a coincidence; it is a structural feature that the standard reply leaves unexplained. The question to address is therefore not "why is the universe not a black hole?"—it is not, for the reasons just given—but "why does the gravitational scale of the observable mass track the observable scale itself, persistently, across regimes?" This is the question Theorem 1 addresses.

1.4. Observable Limits vs Structural Limits

A distinction often glossed over deserves attention here. We commonly say: "We do not know how big the Universe is. We only know the observable universe." We treat this as methodological caution: the observable is a part, the rest is unknown. But this caution hides a deeper structural distinction. The observable universe is a *causal access limit*—defined by how far light has traveled since the Big Bang. The gravitational scale R_g associated with the mass-energy contained in that domain is a *structural limit*—imposed by the Friedmann equations themselves. If the structural limit exceeds the observable domain, then the phrase "the certain minimum is the observable" is no longer innocent: it is incomplete. The key shift is that the certain minimum is not what we observe, but what the theory does not allow us to compress.

1.5. Why Holography Enters the Picture

The connection between gravity and information has been known since the 1970s: Bekenstein showed that black hole entropy scales with area ($S \propto A$), not volume [19]. Hawking made it inevitable with thermal radiation [20]. 't Hooft and Susskind drew the consequence: if maximum entropy scales with area, fundamental information cannot be volumetric [2,3].

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If the observable universe permanently lives near gravitational saturation (as we will show), then this "area law" ceases to be black hole folklore and becomes a cosmological constraint. For the complete history, see Appendix B.

1.6. Precedents and Contribution

The gravitational bound $R_p \lesssim R_g$ and its connection to holography are not new—the relevant precedents include Padmanabhan [1,10], Cai and Kim [11], the holographic-principle literature [2–4,19,20], and Banks and Fischler's holographic cosmology programme [14]. See "Related work and acknowledgement of precedents" for the detailed comparison.

What is new here is the *systematic chain*: from algebraic identity (Theorem 1) to causal exclusion (Theorem 2) to holographic necessity to falsifiable predictions. Closing the chain is the contribution.

1.7. What Is "Strong" Must Be Falsifiable

A theoretical proposal is physics, not mythology, only if it can be refuted by observation. The commitment to falsifiability must be made upfront: if what is about to be said is true, it must leave traces that future observations can record or rule out. If it leaves no traces, it remains narrative; narrative can be useful, but it does not replace physics.

So we commit to empirical risk upfront. The framework naturally leads to large-scale Gaussianity (via CLT), IR suppression in the CMB, and weakness or absence of primordial tensor modes. A sufficiently precise measurement can falsify the framework: that is the point. The proposal is physics, not metaphor—it makes predictions that future observations can rule out.

1.8. Where We Are Going

The path ahead connects several insights into a single logical chain, which the next chapter starts to prove formally.

First, we show that the comparability between observable scale and gravitational scale is not a numerical curiosity—it persists through radiation, matter, and dark energy domination, which means it is *structure*, not coincidence. Second, the seductive interpretation "we live inside a black hole" fails on causal grounds: the structure of FRW spacetime is incompatible with a black hole interior. Third, if information cannot reside in the volume (without violating covariant entropy bounds), it must reside on the boundary, and holography enters not as fashion but as the conclusion that survives once the alternatives have been removed. Fourth, if information is on the boundary, then time cannot be what we thought: it becomes an entropic variable, not a geometric axis. Fifth—and this is the dynamical content of the chain—the near-saturation of Theorem 1 implies that the boundary has no parametrically large frequency gap, which forces the effective bulk dynamics into the sub-Ohmic or near-critical regime of open quantum systems; the past therefore leaves long-tailed traces in the form of non-Markovian memory, and entropic hysteresis appears as a structural consequence of the framework rather than as an additional postulate (Chapter 7).

Corpus Navigation Map (How to Read These Works Together)

To avoid ambiguity about the role of this text: this article is intended as a *logical foundation*. The "how" (mechanism) and the "how much" (quantitative pipeline and fits) are expanded in companion works of the same corpus.

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Table 2. Corpus map. This work establishes *why* holographic description is necessary; companion papers develop *how* it is realized and *how* it is tested.

Topic	Foundation (this)	Mechanism	Laboratory
Holographic necessity	Ch. 2–4	—	—
No-go "universe = BH"	Ch. 3	—	—
Entropic time	Ch. 5 (intro)	[7]	—
CLT and N_{eff}	Ch. 6	[7]	—
Memory kernel K_R	Ch. 7	[7]	—
Observational bridge	Ch. 6–8	[7]	—
Laboratory anchor	mentioned	[7]	[8]

Measured values are taken from Planck 2018 [21], BICEP/Keck [22], and Planck non-Gaussianity constraints [23]. Future sensitivities for r are from LiteBIRD [24] and CMB-S4 [25].

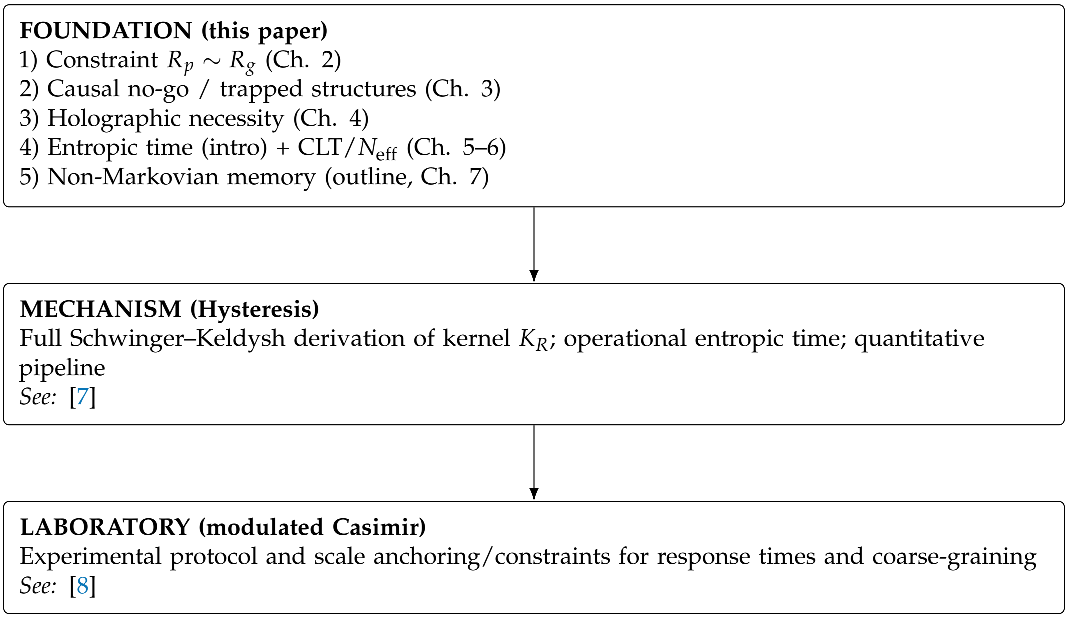

Figure 2. Logical flow of the corpus. Necessity → mechanism → laboratory anchoring.

2. Chapter 2 — The Global Gravitational Constraint

What Friedmann implies (and why it matters)

2.1. The Moment When the Question Stops Being Naive

After the prologue, the question is no longer psychological or didactic. It becomes technical: does there exist, in standard cosmology, a rigorous constraint linking the size of the observable universe to its total mass-energy? Either the constraint exists and is provable, or this is just a numerical impression. The constraint exists.

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Theorem 1 (Global Gravitational Constraint in Flat FRW)

In a flat FRW cosmology ($k = 0$) with monotonically increasing scale factor $a(t)$ and total density $\rho(t)$ satisfying the Friedmann equation

$$H^2(t) = \frac{8\pi G}{3}\rho(t),$$

the particle horizon radius

$$R_p(t) = a(t)\int_0^t \frac{c\,dt'}{a(t')}$$

and the gravitational radius

$$R_g(t) = \frac{2G\,M(t)}{c^2}, \qquad M(t) = \frac{4\pi}{3}\rho(t)R_p^3(t),$$

satisfy the identity relation

$$\frac{R_p(t)}{R_g(t)} = \left(\frac{R_H(t)}{R_p(t)}\right)^2, \qquad R_H(t) = \frac{c}{H(t)}.$$

Furthermore, for expanding universes ($\dot{a} > 0$) we have $R_p(t) \geq R_H(t)$, therefore

$$\frac{R_p(t)}{R_g(t)} \leq 1 \qquad \forall\, t.$$

Proof (inline). Substituting $\rho(t) = \frac{3H^2(t)}{8\pi G}$ in the definition of R_g we obtain

$$R_g(t) = \frac{2G}{c^2}\frac{4\pi}{3}\rho(t)R_p^3(t) = \frac{H^2(t)}{c^2}R_p^3(t) = \frac{R_p^3(t)}{R_H^2(t)}.$$

Therefore $\frac{R_p}{R_g} = \left(\frac{R_H}{R_p}\right)^2$. For $R_p \geq R_H$ it suffices to observe that $a(t') \leq a(t)$ for every $t' \leq t$ when $\dot{a} > 0$, and therefore $1/a(t') \geq 1/a(t)$. We now choose the final interval $[t - H^{-1}(t), t]$, which is contained in $[0, t]$ for all $t \geq H^{-1}(t)$ (the regime of interest for the global gravitational constraint; see remark below); then

$$R_p(t) = a(t)\int_0^t \frac{c\,dt'}{a(t')} \geq a(t)\int_{t-\frac{1}{H(t)}}^t \frac{c\,dt'}{a(t')} \geq a(t)\int_{t-\frac{1}{H(t)}}^t \frac{c\,dt'}{a(t)}$$
$$= \frac{c}{H(t)} = R_H(t).$$

□ *Remark on early times.* For very early epochs in which $t < H^{-1}(t)$, the interval $[t - 1/H, t]$ extends below zero and the inequality above does not apply as written; in that regime one can re-derive the bound directly from the equation-of-state-specific forms of $a(t)$, recovering $R_p \leq R_g$ in all standard cosmologies (radiation- and matter-dominated). The conclusion is robust; the choice of interval in the proof above is the simplest closed form valid for the bulk of cosmic history. See Appendix A.8 for the explicit epoch-by-epoch verification.

Note. Appendix A presents the derivation in more didactic form and a discussion of possible corrections for $k \neq 0$.

2.2. Why $R_p \leq R_g$ Does Not Imply "We Are Inside a Black Hole"

This is where the most common confusion arises: seeing a "gravitational" radius $R_g = 2GM/c^2$ larger than the observable scale and concluding that the Universe must be the interior of a black hole. In FRW cosmology this inference is not correct, because a black hole horizon is not defined by the inequality $2GM/(c^2R) \gtrsim 1$ alone, but by the presence of *trapped surfaces* and a causal structure that generally presupposes an asymptotically flat or at least "stationary" exterior. In FRW, instead, the geometry is dynamic everywhere.

The correct (and invariant) way to say "how massive" a sphere of areal radius R is in a spherically symmetric geometry is to use the Misner–Sharp quasi-local mass $M_{\rm MS}(R)$ [26,27]. In FRW it simply holds $M_{\rm MS}(R) = \frac{4\pi}{3}\rho\, R^3$, and the relevant horizon is the *apparent horizon* R_A, defined by the condition that one of the two radial null expansions vanishes.

Lemma (Apparent Horizon in FRW and Condition $2GM_{\rm MS}/(c^2R) = 1$)

For a flat FRW ($k = 0$) with areal radius $R = a(t)r$ and density $\rho(t)$, the Misner–Sharp mass within R is

$$M_{\rm MS}(R) = \frac{4\pi}{3}\rho(t)\, R^3.$$

The geometric condition identifying the apparent horizon (marginally trapped) is equivalent to

$$\frac{2G\, M_{\rm MS}(R)}{c^2\, R} = 1 \qquad \Longleftrightarrow \qquad R = R_A = \frac{c}{H(t)} = R_H(t),$$

where the last step uses the Friedmann equation $H^2 = \frac{8\pi G}{3}\rho$.

Definition. Throughout, $\rho(t)$ denotes the total energy density entering the Friedmann equation (including matter, radiation, and a possible Λ-like component). The use of the Misner–Sharp mass makes this definition geometric and slicing-invariant in FRW, independently of clustering properties.

Even more explicitly, we can look at the *expansions* of radial future-directed null congruences on a 2-sphere of radius R (here the notation θ_+ "outgoing" and θ_- "ingoing"):

$$\theta_+ = \frac{2}{R}(HR + c) > 0, \qquad \theta_- = \frac{2}{R}(HR - c).$$

For an expanding Universe ($H > 0$) then:

- if $R < R_H$ we have $\theta_+ > 0$ and $\theta_- < 0$ (*normal region*): outgoing rays increase R, ingoing ones decrease it;
- if $R = R_H$ we have $\theta_- = 0$ (*apparent horizon*);
- if $R > R_H$ we have $\theta_+ > 0$ and $\theta_- > 0$ (*anti-trapped region*): *both* future bundles tend to increase R.

A true "black hole region" would require instead $\theta_+ < 0$ and $\theta_- < 0$ (trapped), i.e., a collapsing geometry ($H < 0$) or a different causal structure [28]. Therefore the constraint of Theorem 1—which is ultimately a rewriting of $R_p \geq R_H$—does not say "we are trapped": it says that the scale of causally connected regions in FRW grows in such a way as to make inevitable a global comparison between density and horizons. It is precisely this inevitability (not the analogy with Schwarzschild) that motivates the question about the *non-fundamentality* of the bulk.

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Figure 3. Difference between $R_H = c/H$ (local Hubble scale) and R_p (particle horizon, causally accessible scale). Theorem 1 links R_g to R_p, not to R_H; the comoving particle horizon and the comoving Hubble radius are distinct quantities, even though they coincide in order of magnitude for much of cosmic history.

Figure 4. Behaviour of $R_p(t)$ and $R_g(t)$ (panel a) and of the ratio R_p/R_g (panel b) in a reference ΛCDM model with $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$, $H_0 = 67.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Planck 2018). In each panel the bound $R_p \le R_g$ is satisfied across the entire cosmic history, with the ratio remaining close to unity for an extended interval of redshifts. The figure illustrates the algebraic identity of Theorem 1 in a concrete background; it is not a microphysical derivation of holography, which follows from the combined argument of Chapters 2–4.

The constraint is hidden in plain sight under the eyes of anyone who uses the Friedmann equations daily.

2.3. FRW: The Minimal (and Unavoidable) Context

We work in the most conservative possible context: a homogeneous and isotropic Universe, described by the Friedmann–Robertson–Walker metric, with zero spatial curvature ($k = 0$), in agreement with current observations.

The global dynamics is governed by the Friedmann equation:

$$H^2(t) = \frac{8\pi G}{3}\,\rho(t), \qquad H(t) = \frac{\dot a(t)}{a(t)}. \tag{1}$$

where:

- $H(t) = \dot a(t)/a(t)$ is the Hubble parameter;
- $\rho(t)$ is the total energy density (radiation + matter + dark energy).

This equation is already, in itself, an important statement: the geometry of the Universe is fixed by its global energy content.

We are not making exotic assumptions. We are using standard cosmology.

Table 3. Operational notations (one line of physics per symbol). Throughout the manuscript we distinguish between *causal* scales (related to light and horizons) and *gravitational* scales (related to mass-energy).

Symbol	Operational definition
$R_p(t)$	particle horizon radius (the *radius of the observable Universe* at time t).
$R_H(t) = c/H(t)$	Hubble radius (useful as local scale; does *not* generally coincide with a causal horizon).
$M(t) = \frac{4\pi}{3}\rho(t)\,R_p^3(t)$	mass-energy contained within $R_p(t)$ (homogeneous FRW model).
$R_g(t) = 2GM(t)/c^2$	gravitational radius associated with $M(t)$.
$A(t) = 4\pi R_p^2(t)$	area of the causal "screen" associated with $R_p(t)$.
$N \sim A/\ell_P^2$	holographic microstatistical count (informational capacity of the screen).
$N_{\rm eff}$	*effective* number of quasi-independent patches contributing to the reconstructed bulk (what enters the CLT).

2.4. Which "Size" of the Universe? An Operational Choice

Before proceeding with the comparison, an operational clarification is necessary: speaking of "size of the Universe" without specifying which horizon is a conceptual shortcut. In cosmology there exist

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multiple scales, and confusing them is the fastest way to say something false with confidence; we therefore distinguish them explicitly.

2.4.1. Hubble Horizon

$$R_H(t) = \frac{c}{H(t)}.$$

This is a local, dynamic scale, related to the instantaneous expansion. It is not a true causal horizon.

2.4.2. Particle Horizon

This is the true causal scale: the maximum distance from which light signals could have reached us since the beginning of expansion. If we want to talk about the "observable Universe" unambiguously, this is the correct definition, and it is the one used throughout this paper.

Operational note. Although we adopt the particle horizon as the operational definition of "observable", the core inequality and the causal argument are robust under any causal scale bounded between the Hubble and particle horizons in an expanding FRW; changing the operational radius only shifts order-one factors and does not alter the logical conclusion.

2.5. The Mass-Energy of the Observable Universe

Once the scale is defined, the mass-energy contained within the particle horizon is a well-defined quantity. We do not mean "the mass of the Universe," a notion that is not well-defined in general; we mean the mass-energy that is causally accessible to a comoving observer at time t. This is all that is needed for the argument that follows.

2.6. The Gravitational Radius: Not Yet a Black Hole

To every distribution of mass-energy, General Relativity associates a natural gravitational scale:

$$R_g(t) = \frac{2GM(t)}{c^2}.$$

Here it is essential to be clear: we are not saying that the Universe is a black hole. We are only associating a geometric scale to a mass-energy, as is done everywhere in gravity.

The analysis proceeds on solid ground: we are using standard definitions, without premature interpretations.

Weak requirement. For ΛCDM parameters within current observational ranges, the ratio $R_{\mathrm{p}}(t)/R_g(t)$ remains $\mathcal{O}(1)$ over cosmic history; the argument only requires that the ratio is not parametrically small. We explicitly separate this weak requirement from any stronger claim of exact saturation.

3. Chapter 3 — The Causal No-Go Theorem

Why the Universe cannot be the interior of a black hole

3.1. The Most Seductive (and Most Wrong) Shortcut

Having arrived at the constraint

$$R_{\mathrm{observable}}(t) \leq R_g(t) \quad \forall\, t,$$

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the most common reaction is to conclude that we live inside a black hole. The phrase has a long history in popular and speculative literature, because it seems to close the question in one stroke: if the radius is comparable to the gravitational radius, the geometry must be that of a black hole interior. we argue that this shortcut, however intuitive, is wrong on causal grounds. In relativistic physics, comparing two numbers is not enough: what matters is how spacetime is causally connected. And the causal structure of a black hole interior is one of the most robust results of General Relativity, as we recall below.

3.2. What "Interior of a Black Hole" Really Means

When we say "interior of a black hole" we are not using a metaphor. We refer to a precise geometric structure, well defined and studied in detail since the 1960s. In the simplest case—the Schwarzschild black hole—the metric exhibits a fundamental feature: beyond the horizon, the roles of space and time are exchanged. The radial coordinate becomes timelike, and moving toward smaller radii is no longer a choice but a destiny. As a consequence, all future-directed timelike geodesics terminate at the singularity in finite proper time; the future is closed, and spacetime is future-incomplete. This is a causal property, not a coordinate artifact, and it holds not only for Schwarzschild but also for Kerr, Reissner–Nordström, and for any classical black hole satisfying the standard energy conditions.

3.3. The Future of the Observed Universe: An Opposite Structure

The picture for the observed Universe is markedly different. Comoving observers in FRW follow future-complete timelike geodesics: they are not forced to encounter a future singularity, they see proper distances increase, and they witness a global expansion. The cosmological future, at least in the classical post-big-bang description, is open. This is not a dynamical detail but a global property of the causal structure of FRW spacetime.

3.4. Penrose Diagrams: When Images Matter

It is worth pausing here, because this is one of the points where a drawing is worth more than a thousand formulas. A Penrose diagram compactifies infinity and makes causal relations visible. In the diagram of a black hole the horizon is an inclined line, the singularity is an inevitable future timelike line, and every internal observer is "pulled" toward that line. In the diagram of an expanding FRW universe, by contrast, the initial singularity (Big Bang) is in the past, the future opens toward infinity, and there is no inevitable causal death line in the future. These two diagrams are not deformations of each other: no smooth transformation makes them equivalent.

Figure 5. Penrose-style comparison of causal structure. In the interior of a classical black hole, future-directed timelike geodesics terminate on a future singularity (future-incomplete); in FRW with $H > 0$, future-directed timelike geodesics extend indefinitely (future-complete). The two geometries are not diffeomorphic, so the inequality $R_{\rm obs} \sim R_g$ does not authorize identification of the Universe with the interior of a black hole. Thermodynamic analogies between cosmological horizons and black-hole horizons remain valid; the no-go concerns only the geometric identification.

This point excludes naive interpretations based solely on numerical analogies.

3.5. Statement of the No-Go Theorem

The result can now be stated formally.

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Theorem 2 (Causal No-Go)

Let $(\mathcal{M}, g_{\mu\nu})$ be a globally hyperbolic spacetime that admits:

(i) a congruence of future-complete timelike geodesics (comoving observers have infinite future);
(ii) a global expansion ($H > 0$, with $H = \dot{a}/a$ the Hubble parameter).

Then $(\mathcal{M}, g_{\mu\nu})$ is not diffeomorphic to the interior of the horizon of a classical black hole (Schwarzschild, Kerr, Reissner–Nordström or any solution with an inevitable future singularity).

Proof (outline).

The proof follows from the standard causal structure of General Relativity [17,18]:

1. In the interior of a classical black hole, all future-directed timelike geodesics terminate on the singularity in finite proper time. This is the content of the Penrose–Hawking singularity theorems [17,18].
2. By definition, a spacetime with future-complete geodesics does not have this property: observers can exist for arbitrarily long proper time.
3. Geodesic completeness is a causal invariant: it is preserved under diffeomorphisms.
4. Therefore a future-complete spacetime cannot be diffeomorphic to a future-incomplete one. □

Technical note.

Condition (ii) serves to exclude contracting cosmologies ($H < 0$) that could terminate in a Big Crunch. The observed Universe today ($H_0 > 0$, acceleration $\ddot{a} > 0$) satisfies both conditions.

This theorem:

- does not depend on specific dynamical details;
- does not depend on the nature of dark energy;
- does not depend on quantization of gravity;
- does not depend on exotic initial conditions.

It depends only on causal structure, and its strength derives from this minimality.

Qualifier. The no-go targets classical black-hole interiors with inevitable future incompleteness under standard energy conditions. If one adopts a non-singular ("regular") black-hole interior, one is no longer comparing with classical GR black holes but with an explicitly modified, exotic or quantum-corrected causal structure—precisely the kind of additional physics the present no-go is meant to isolate as non-minimal.

3.6. Where Many Previous Proposals Fail

Over the years various ideas of "Universe as black hole" or "Universe born from a black hole" have been advanced. Pathria [12] was among the first to raise the question of whether the observable universe could be identified with the interior of a black hole; Stuckey [13] analyzed the same question through the structure of Penrose diagrams and reached the same negative conclusion that the present Theorem 2 formalizes. Subsequent revivals of the proposal, including the cosmological natural selection of Smolin [29], the torsion-bounce cosmology of Popławski [30], the regular black-hole interiors of Hayward [31] and Frolov [32], and the recent, quantitatively developed "Black Hole Universe" model of Gaztañaga [33]—in which the observable Universe is the interior of a bounded FLRW region with $R < r_S$—share one of the following structural problems.

They modify causal structure without acknowledging it openly. The classical interior of a Schwarzschild black hole has a definite causal orientation; alternative proposals typically replace this with a different structure (regular interiors, bounces, non-orientable identifications) and then claim that the original "universe inside a black hole" interpretation still holds. The original interpretation does not survive the modification.

They invoke new physics before the existing physics has been exhausted. Quantum corrections, modifications of the energy conditions, or post-classical bounces are introduced as the resolution; this is legitimate as a research direction, but it is not a resolution of the question stated within classical GR. The present argument is more conservative: it asks what classical GR alone permits, and concludes that the black-hole interpretation is excluded at that level before any new physics is invoked.

They confuse numerical analogy with geometric identity. The comparability $R_{\text{obs}} \sim R_g$ is a statement about scales; the identity "universe = black-hole interior" is a statement about diffeomorphism class. Theorem 2 separates the two: the former is permitted (and in fact forced by Theorem 1); the latter is excluded.

The approach adopted here therefore proceeds in the opposite order: first establish, using only classical GR, what cannot be true, and then ask what minimal extension is required to accommodate what remains.

3.7. The Paradox That Remains (and Is Productive)

At this point we are in an apparently paradoxical situation: the observable Universe is always smaller than the gravitational radius associated with its mass; yet it is not a black hole; yet gravity is strong enough to impose a global bound.

This is not a problem with a quick exit. The situation is structurally constrained: gravity, covariant entropy bounds, and causal structure jointly impose a tension that cannot be resolved by adding one more observation or one more parameter—it requires the framing itself to be reconsidered.

When standard physics, followed carefully, points in a direction that was not anticipated at the time the formalism was written down, the natural response is to follow the direction rather than to soften it.

3.8. Chapter Summary

At this point the analysis can proceed without terminological ambiguity. The reasoning is straightforward: if the information cannot be stored volumetrically (because of the covariant entropy bound), and the bulk cannot collapse into a black hole (by Theorem 2), then the information must reside elsewhere. That "elsewhere" has a precise name, known for decades: *holography*. This is the subject of Chapter 4.

4. Chapter 4 — Holography as Necessity

When the only way out is not a hypothesis, but a consequence

4.1. The Paradox, Formulated Without Escape Routes

Recap, without attenuation. The observable Universe always satisfies the constraint $R_{\text{obs}}(t) \leq R_g(t)$ as a direct consequence of the Friedmann equations. This constraint does not imply collapse, nor does it describe the interior of a black hole, by causal no-go. However, the constraint is gravitational and physical: it is not a coordinate artifact nor a numerical coincidence.

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At this point physics is in a clear position: there exists a structural limit to the information contained in the observable Universe, but such information cannot be contained volumetrically and cannot collapse. This is the constraint the rest of the chapter must accommodate. It cannot be resolved with local dynamics.

The analysis leads to a stringent constraint: "If you cannot move the problem in space, you cannot move it in time, and you cannot change causality… then you must change where the information resides."

4.2. A Lesson Physics Has Already Learned (at Great Cost)

This point is not new in physics. It was one of the strongest theoretical shifts of the 20th century.

When Bekenstein proposed that black hole entropy was proportional to the horizon area, the reaction was disbelief. When Hawking demonstrated that black holes radiate like black bodies, disbelief became necessity.

The combined result was devastating for classical intuition: the maximum entropy containable in a gravitational region does not scale with volume, but with the area of its boundary. This is a gravitational thermodynamic law, not a stylistic preference.

Bousso's covariant entropy bound [4] provides a rigorous basis for this dichotomy: for any spacelike surface, the entropy traversing a light cone is limited by the surface area in Planck units. In FRW, this implies that a volumetric description of fundamental information is inconsistent with causal bounds.

Explicit application to the particle horizon.

Since the covariant bound is formulated for light-sheets rather than for spatial surfaces, it is worth stating explicitly how it applies here, because the step is sometimes left implicit. Consider, at cosmic time t, the spherical surface B of areal radius $R_p(t)$ that bounds the observable region of a comoving observer. The bound requires a light-sheet: a null hypersurface generated by light rays orthogonal to B with non-positive expansion. In an expanding FRW spacetime, the past-directed ingoing null congruence emanating from B has negative expansion ($\theta < 0$) as it converges toward the observer's worldline, and therefore constitutes an admissible light-sheet L. This past light-sheet is precisely the past light cone that defines the particle horizon: B is the boundary of the causal past of the observer up to t, so the construction is not an additional assumption but the geometric content of "observable region" itself. Bousso's bound then states

$$S[L] \leq \frac{A(B)}{4\ell_P^2} = \frac{\pi R_p^2}{\ell_P^2},$$

where $S[L]$ is the entropy crossing the light-sheet, i.e. the entropy of everything the observer can have received. A genuinely volumetric account of the fundamental degrees of freedom would give $S \sim (R_p/\ell_P)^3$, which exceeds the bound by a factor $\sim R_p/\ell_P \sim 10^{61}$ at the present epoch. The volumetric account is therefore not merely disfavoured; it is excluded by the covariant bound applied to the very light cone that defines the observable Universe. This is the explicit form of the dichotomy used throughout the rest of the paper.

And if it is true for the extreme case of a black hole, then one might ask: why should it cease to be true in a Universe that permanently lives in a condition of global gravitational saturation? Within the standard framework there is no clean answer that does not involve holography—which is the path explored in the next section.

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4.3. *From "Might Be" to Argued Option: Explicit Exclusion of Alternatives*

Holography in cosmology is often presented as a possibility, an inspiration, an analogy with AdS/CFT. The argument here is stronger: once the alternatives are taken seriously, they fall away, and what remains is the holographic option. Let us work through the alternatives explicitly.

Alternative 1: Volumetric description with bound respected.

Impossible. Bousso's covariant bound [4] states that the entropy traversing any light cone is limited by the surface area in Planck units:

$$S \leq \frac{A}{4\ell_P^2}.$$

A volumetric description with $S \propto V$ would violate this bound when $R \sim R_g$, exactly the situation imposed by Theorem 1. The bound is a widely studied covariant entropy bound, strongly motivated by black-hole thermodynamics (Bekenstein–Hawking) and consistency with causal structure (Bousso); within semiclassical gravity it provides the natural statement of gravitational information accounting.

Alternative 2: Modification of gravity that changes the bound.

Possible in principle, but:

- Requires new physics not observed (no deviation from GR has been measured on cosmological scales).
- Known modifications (f(R), scalar-tensor, Horndeski) do not eliminate the entropy bound; at most they shift it.
- The bound has *thermodynamic* origin (Bekenstein), not only gravitational: changing Einstein's equations is not enough.

This alternative violates the principle of parsimony: it introduces new physics to avoid a conclusion that already follows from existing physics.

It is worth being explicit about a potential circularity here, since a proponent of modified gravity could object that the covariant entropy bound is itself derived from general relativity, so using it to exclude modifications of GR begs the question. The objection is fair, and the honest reply is to state the conditional nature of the whole argument. We do not prove that modified gravity is impossible. We prove that *if* one accepts general relativity together with black-hole thermodynamics and the standard causal structure of FRW, *then* the holographic description is the option that adds no further postulates. A proponent of modified gravity is free to reject the premise; but doing so requires introducing new degrees of freedom that have not been observed, which is precisely the parsimony cost this framework avoids. The argument is therefore conditional, not absolute, and the conditionality is part of its content rather than a hidden weakness.

Alternative 3: Volumetric degrees of freedom with non-local correlations.

Apparently different from holography, but in reality *equivalent*. If degrees of freedom are formally volumetric but correlated in such a way that effective entropy scales with area, then:

- the *independent* information is proportional to area, not volume;
- the "volumetric" description is redundant;
- we have redefined "volumetric" in a holographic way.

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This is not an alternative: it is holography with a different name. Constructive realizations of this idea—in which bulk geometry is reconstructed from entanglement patterns on a tensor network or boundary state—include the MERA-based approach of Cao, Carroll and Michalakis [34] and the entanglement-geometry programme initiated by Van Raamsdonk [16]. These programmes are constructive instances of the same conclusion the present argument reaches by necessity.

Alternative 4: Cosmic coincidence.

Excluded by Theorem 1. The relation $R_p/R_g = (R_H/R_p)^2$ is not a coincidence of the current epoch: it is an algebraic identity valid in *every* cosmic epoch (radiation, matter, Λ). A coincidence that persists for 13.8 billion years through three different dynamical regimes is not a coincidence: it is a structure.

Alternative 5: Coordinate artifact.

Excluded. Theorem 1 uses invariant quantities:

- R_p is defined by causal structure (null geodesics);
- M is the Misner–Sharp mass, a quasi-local and covariant quantity;
- $R_g = 2GM/c^2$ is a physical scale, not a coordinate.

Changing coordinates does not eliminate the constraint.

What remains. Once the alternatives fall away, what survives is this:

The information describing the observable Universe resides on a holographic boundary, not in the volume.

This is not a speculative leap. It follows from standard cosmology (Friedmann) plus causal structure (no-go) plus gravitational thermodynamics (Bekenstein–Hawking–Bousso). No new physics is needed; what is needed is taking the existing physics seriously enough to follow its consequences.

Epistemic note: "necessary" vs "best supported"

Some precision about the strength of the argument. The exclusion of alternatives shows that holography is the best-supported reading of the constraint within standard physics, not that it is logically necessary in the sense of mathematical proof.
A skeptic can always postulate unknown physics that changes the rules. What the chain established here shows is that, taking GR plus thermodynamics plus causality at face value, the holographic reading is the one that does not require additional assumptions.
The appropriate epistemic status is therefore: strongly motivated within the assumptions, not mathematically forced.

4.4. What Kind of Boundary? (and Why AdS Is Not Needed)

No duality assumption. We do not assume a specific dS/CFT duality. The argument only requires a covariant holographic accounting (entropy/DOF scaling with area) consistent with causal structure; no detailed boundary QFT or AdS embedding is needed for the logical step established here.

A legitimate objection to invoking holography in cosmology is that the best-understood holographic correspondence is AdS/CFT, while the Universe is not asymptotically AdS but rather nearly de Sitter. The objection is correct as a description of the state of the art, but it confuses a particular realization with the underlying principle. The holographic principle in its general formulation does not say "every universe is dual to a CFT in AdS"; it says that the fundamental description of a gravitational region is encodable on

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its boundary. AdS/CFT is the most studied realization, but it is not the only kind of boundary one can consider.

Figure 6. Conceptual scheme of cosmological holography. The fundamental degrees of freedom are located on the causal boundary; the bulk is reconstructed through correlations among boundary degrees of freedom. Information scales with the boundary area ($A \sim R_p^2$), while volume is an emergent description. The figure illustrates the accounting argument of Chapter 4 and does not commit to a specific AdS/CFT realization.

In cosmology, the relevant boundary is not a static spatial frontier, but a causal horizon: an informational boundary, not a wall.

Relation to dS/CFT.

It is worth being explicit about the relation between the present argument and the dS/CFT proposal of Strominger [35] and the dS/CFT correspondence developed by Maldacena [36]—both descending from the foundational AdS/CFT correspondence of Maldacena [37]. Those proposals attempt to formulate an exact duality between a quantum theory on the de Sitter boundary and gravitational dynamics in the bulk, by analogy with AdS/CFT. The present argument is strictly weaker: it does not assume any specific duality, does not require a boundary CFT with definite operator content, and does not commit to whether the universe is asymptotically de Sitter. What it claims is that, within standard GR plus covariant entropy bounds, the gravitational information accounting on a causal screen must scale with area; the specific quantum description of that screen is left open. If a future formulation of dS/CFT succeeds in producing a complete duality, the present framework is compatible with it as a low-energy/coarse-grained limit; if dS/CFT fails or is shown to be inapplicable to realistic cosmologies, the present argument is unaffected, because it does not depend on it.

A key point is that the "boundary" we refer to is an *informational/operational* boundary: it is defined by causal accessibility, not by a particular coordinate choice, and not necessarily by the presence of a static event horizon. For this reason, the particle horizon radius R_p is the natural scale for information accounting in our argument: it is directly constructed from null geodesics and encodes the maximal region that can be put in causal contact with an observer up to a given cosmic time.

Observer dependence and the cosmological principle.

A reasonable objection is that the particle horizon depends on the observer: different comoving observers at the same cosmic epoch have different R_p centred on themselves. Does the framework therefore lose objectivity? The answer is that observer dependence in this sense is precisely what one expects of a relational, informational description, and is compatible with the homogeneity assumption of FRW. For any two comoving observers A and B at the same cosmic time, the local geometry, the matter content, and the gravitational identity $R_p/R_g = (R_H/R_p)^2$ are identical; the boundaries $\partial\mathcal{O}_A$ and $\partial\mathcal{O}_B$ are diffeomorphic, with the same area scaling and the same effective number of degrees of freedom $N_{\rm eff}$. What differs is which region of the boundary each observer is causally connected to, not the structure of the boundary itself. The framework is therefore observer-relational rather than observer-arbitrary: every comoving observer reconstructs an equivalent bulk from her own causal screen, and the cosmological principle is recovered as the statement that all these reconstructions are isomorphic.

Other horizon notions (apparent horizon, event horizon) can be relevant in complementary contexts, but they do not serve the same operational role here. In particular, the event horizon is future-defined and may not exist in general cosmologies, while the apparent horizon is tied to local expansion properties and

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can vary in ways that are not directly aligned with "what has been causally accessible so far". By contrast, R_p is the minimal and robust choice that makes the paradox operational: it compares a causal scale (R_p) to a quasi-local gravitational scale (R_g) built from the enclosed Misner–Sharp mass.

The framework therefore approaches the cosmological boundary using the natural tools of covariant entropy bounds, apparent horizons, and null-expansion surfaces. We are not importing AdS/CFT; we are recognizing that the appropriate language for the cosmological information accounting is that of area.

4.5. The Reconstruction Mechanism: From Entanglement to Geometry

At this point a legitimate question arises, often formulated as: "An optical hologram needs a laser to be read. Through what mechanism does a holographic universe generate 3+1 dimensional spacetime?"

Entropy meaning. Whenever we refer to entropy on the boundary we mean a renormalized/coarse-grained entropy relevant to distinguishable macrostates (i.e. entropy differences under physical coarse-graining), not the raw UV-divergent entanglement entropy of continuum QFT. The area scaling is used as a statement about the counting of effective degrees of freedom, not as a literal continuum entropy.

The question is crucial because it distinguishes metaphor from physical argument.

The optical hologram as imperfect metaphor.

In a traditional hologram, a 2D plate contains interference patterns; a coherent laser beam illuminates the plate; the diffracted light reconstructs the 3D image. The "reconstruction mechanism" is the coherent light, and requires an external agent (the observer with the laser).

In cosmological holography there is no external laser. The mechanism is intrinsic: it is the **quantum entanglement** between degrees of freedom on the boundary.

Entanglement as geometry: the Ryu–Takayanagi result.

The connection between entanglement entropy and geometry has been one of the central developments in theoretical physics of the last twenty years. The Ryu–Takayanagi formula [15] states that, in a holographic context:

$$S_A = \frac{\text{Area}(\gamma_A)}{4G\hbar}, \tag{2}$$

where S_A is the entanglement entropy of a region A on the boundary, and γ_A is the minimal surface in the bulk that "hangs" from the boundary of A.

The content of Eq. (2) is concrete: the *area* of a surface in spacetime emerges from the *structure of entanglement* on the boundary. Geometry is not an input; it is an output of quantum correlations.

Spacetime as a map of entanglement.

Van Raamsdonk [16] synthesized this result provocatively:

> *"Spacetime is stitched together by quantum entanglement."*

In operational terms:

- If two regions of the boundary are highly entangled ⇒ they are "close" in the bulk.
- If they are weakly entangled ⇒ they are "far apart."
- If entanglement is cut ⇒ spacetime disconnects.

This provides the "illumination mechanism" that was missing from the holographic metaphor:

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1. The degrees of freedom on the cosmological screen are entangled with each other.
2. The *structure* of this entanglement *defines* the geometry of the bulk: short-range correlations $\rightarrow$ local structure; long-range correlations $\rightarrow$ global structure (curvature, expansion).
3. No external agent is needed: the cosmological hologram is *self-reconstructing*. The quantum correlations on the boundary *are* the interior spacetime.

Time as the dynamics of entanglement.

In our framework, the entropic time τ_S (Chapter 5) acquires a natural meaning: it is the parameter that tracks the evolution of the entanglement structure on the boundary. The "passage of time" corresponds to the change in correlations—and the increase in horizon entropy reflects the growth of complexity of these correlations.

In other words: boundary and bulk are not two separate entities, with one "projecting" the other. They are *two descriptions of the same physical system*, like wave and particle are two descriptions of the same photon. The question "what illuminates the hologram?" presupposes a dualism that the holographic principle dissolves.

4.6. The Consequence: The Volume Becomes Derived

If fundamental information is on the boundary, then what happens "inside" cannot be primary. The three-dimensional space we perceive is not the fundamental support of physics, but an emergent description of entropic relations. Volume is not where information lives; it is where information manifests as effective dynamics. This is the same conceptual revolution that transformed temperature from substance to statistics, and pressure from force to collective emergence. The same now happens with space.

4.7. Internal Consistency Check

At this point the analysis satisfies the following consistency criteria: the gravitational bound is respected (Theorem 1), causality is preserved (Theorem 2), no new physics has been invoked before necessary, the historical connection with black-hole entropy is recovered (Bekenstein–Hawking–Bousso), and the volumetric alternative is excluded explicitly (Sec. 4.3). This internal consistency is a necessary, not sufficient, requirement for a viable framework.

4.8. But Then: What Is Time?

Once information is on the boundary, a question becomes inevitable: what are we really calling "time" in the interior? If space is emergent, time—which measures changes of configurations—cannot be an independent fundamental parameter. The discussion of entropy, arrow of time, and cosmic history as informational accumulation is the task of Chapter 5, where the entropic-hysteretic paradigm enters not as an addition but as a structural consequence of cosmological holography.

5. Chapter 5 — Time as an Entropic Variable

Scope note. Chapters 5–7 are included as a bridge to companion works: the logical necessity of a boundary description established in Chapters 2–4 does not depend on adopting entropic time or hysteresis. Readers may treat these chapters as an optional constructive extension, with full dynamical development delegated to the companion papers.

In a holographic description, time cannot be treated as fundamental in the same sense as a coordinate of GR.

5.1. *The Question Physics Avoids (but Cannot Avoid Forever)*

Once we have accepted that the fundamental information of the Universe is not volumetric but resides on a holographic boundary, and that internal space is an emergent description, a question becomes inevitable: what is time? Not in the sense of how we measure or coordinate it, but in the sense of what it physically represents. For centuries time has been treated as a background: first absolute, then geometric, then relativistic, but in every case taken as given. If space is not fundamental, the parallel question for time becomes hard to dismiss.

5.2. *Time in General Relativity: Geometry, Not Explanation*

In General Relativity, time is a coordinate of spacetime—formally well defined and operationally indispensable, yet silent on a number of structural questions. GR tells us how time curves, but not why there is an arrow, nor why the past weighs on the present, nor why the Universe has a history. The well-known paradox is that the fundamental equations are (almost) time-symmetric while the observed Universe is not. This is not a statistical detail but a conceptual gap that any informational reformulation of cosmology must address.

5.3. *If Information Is on the Boundary, Time Cannot Be an Axis*

In the holographic framework developed in previous chapters, the boundary of the observable Universe encodes information, evolves, and accumulates entropy. The crucial point is the following: if information grows, there exists an order of states, and what we call "time" becomes a measure of that order. Time is no longer an external axis or a fundamental coordinate: it is an emergent variable that counts how much history has been written. Time ceases to be geometry and becomes entropic accounting. This conclusion does not arise from philosophy but from the informational structure of the system.

5.4. *The Key Idea: The Past Really Weighs*

We can now formulate, without vague metaphors, the intuition that motivated this corpus from the beginning: the past is not simply "what is no longer there," but an informational substrate that weighs on the present. In a holographic Universe, every configuration leaves traces, the traces are not erased, and the set of traces defines the current state. This is the physical meaning of entropic hysteresis: not psychological memory, but a structural property of the system.

5.5. *Time as an Entropic Function*

5.5.1. Operational Parametrization of Entropic Time (Reference to Corpus)

In the corpus, "entropic time" is not a metaphor but a *monotonic variable* constructed from the entropy of the apparent horizon. An operational definition (developed and used quantitatively in the companion papers [7]) is:

$$\tau_S(t) \equiv \int_0^t dt' \, \frac{dS_{\rm hor}}{dt'} = S_{\rm hor}(t) - S_{\rm hor}(0), \tag{3}$$

where $S_{\rm hor} = A_{\rm hor}/(4\ell_P^2)$ and, for flat FRW, $A_{\rm hor} = 4\pi R_A^2$ with $R_A \simeq c/H$. In the companion framework, an explicit expression of $dS_{\rm hor}/dt$ in terms of energy content (density and pressure) and thus of $w(z)$ is discussed, directly connecting the monotonicity (or saturation) of τ_S to observational measurements [7].

To make explicit the connection between τ_S and cosmological dynamics, we observe that in flat FRW the apparent horizon coincides with $R_H = c/H(t)$, thus $S_{\rm hor}(t) \propto H^{-2}(t)$. In particular,

$$\frac{dS_{\rm hor}}{dt} = -\frac{2\pi c^5}{G\hbar}\frac{\dot{H}}{H^3}. \tag{4}$$

Using the acceleration equation for a total effective fluid in flat FRW,

$$\dot{H} = -\frac{3}{2}\big(1 + w_{\rm eff}(t)\big)H^2, \qquad w_{\rm eff} \equiv \frac{p_{\rm tot}}{\rho_{\rm tot}c^2}, \tag{5}$$

we obtain

$$\frac{dS_{\rm hor}}{dt} = \frac{3\pi c^5}{G\hbar}\frac{1 + w_{\rm eff}(t)}{H(t)}. \tag{6}$$

The monotonicity of τ_S therefore requires $w_{\rm eff} > -1$ (no "phantom" regime), making transparent how the entropic parameter is directly linked to the expansion history. For an extended discussion of "time as internal variable" and the connection with the problem of time, see [7], Sec. IV.F.

Note on non-circularity of the definition.

At first glance, the definition $\tau_S(t) = \int_0^t dt'\, dS_{\rm hor}/dt'$ seems circular: we use t to define τ_S, then claim that "time is entropic." The circularity is only apparent:

- t is the **FRW coordinate time**: a geometric label always defined in the metric, without intrinsic thermodynamic content.
- τ_S is the **physical/entropic time**: a reparametrization that makes explicit the informational content of evolution.
- The **arrow of time** emerges from the monotonicity $d\tau_S/dt > 0$, which follows from $dS_{\rm hor}/dt > 0$ (generalized second law).

In other words: t exists as a coordinate, but τ_S is what gives physical meaning to the ordering of states. The analogy is with classical thermodynamics: the "time" of the thermostat is not the spatial coordinate of the clock hand, but the entropy that grows.

Use in this paper. Here τ_S serves to clarify the conceptual point: *if* fundamental information is on the boundary, then a natural evolution variable is one that grows (or saturates) with horizon entropy, while coordinate time remains a geometric label. The observable consequences and dynamical implementation are deferred to the companion papers [7].

At this point we can formulate explicitly the natural relation between time and entropy:

$$t \;\equiv\; \mathcal{T}(S).$$

This compact relation is the conceptual statement; its operational realization is the entropic time $\tau_S(t)$ defined in Eq. (3), which is the form actually used in computations throughout this paper and in the companion work. The two notations refer to the same object: $\mathcal{T}$ is the function that maps boundary entropy to a monotonic evolution parameter, and $\tau_S(t)$ is its explicit form for flat FRW in terms of horizon entropy. In what follows we use $\tau_S(t)$ when a calculation is involved and $\mathcal{T}(S)$ when the conceptual statement is what matters.

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Figure 7. Parametrization of cosmic evolution through horizon entropy S_H. The curve is monotonically increasing ($dS_H/dt > 0$), so that the entropic time τ_S defined in Eq. (3) provides a well-defined alternative to the geometric coordinate t. The figure illustrates the conceptual statement of Chapter 5; the dynamical content—how entropy growth couples to matter and radiation—requires the equations of state and is developed in [7].

where:

- S is the total entropy encoded on the holographic boundary,
- $\mathcal{T}$ is a monotonically increasing function.

There is no need to specify its form immediately. It is only necessary to recognize one thing:

Time grows because entropy grows, not the other way around. The conceptual inversion is in this asymmetry.

5.6. The Arrow of Time Is Not a Problem: It Is a Definition

In the standard framework, the arrow of time is an open problem. In the entropic-holographic framework, it is closer to a structural feature of the description. If the present state includes all accumulated information, and the future state will include more, the future is defined as the direction of entropic growth. No special initial conditions are required, and no inflation is needed to "explain" the arrow. The arrow simply is the entropic direction.

5.7. Inside the Universe: What Is There, Then?

The question the reader has been carrying for pages is: if the Universe is described on the boundary, what is inside? The answer is now clear and surprisingly sober: inside there is a history. Not a container of primary information, but a dynamic projection of entropic relations. Galaxies, fields and particles are effective modes through which boundary information organizes itself internally. The language developed in the broader corpus—entropons as quanta of entropic information, collective excitations of the entropic field, and internal dynamics as hysteretic response to accumulated history [9]—fits naturally in this picture; we do not formalize it here.

5.8. Consistency Check

The analysis at this point is consistent with the framework established in earlier chapters: space is not fundamental (in line with holography), information on the boundary respects the area law, the emergent time variable accounts for the arrow of time, no causal violation is introduced, and no inflation is invoked by force.

5.9. Where All This Takes Us

We are now ready for the next structural step. If time is entropic, space is emergent, and the Universe is described by an informational boundary, then several standard "solutions" of cosmology (inflation included) must be re-evaluated—not rejected by ideology, but downsized by necessity. Chapter 6 addresses how isotropy, Gaussianity and perturbation structure descend naturally from the proposed framework, and how observables (amplitude, phase coherence, non-Gaussianity) become consistency tests of the boundary-to-bulk mapping.

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Bridge to Chapter 6.

If the effective temporal variable is the entropic parametrization τ_S introduced in Eq. (3), then what in standard language we would call "initial conditions" of the bulk at $\tau_S = 0$ is not an arbitrary input: it is constrained (coarse-grained) by the informational state on the boundary. In the following chapter we exploit precisely this point: assuming a mixing of many quasi-independent contributions (in number $N_{\rm eff}$) we show how Gaussianity and quasi-isotropy emerge naturally via the Central Limit Theorem, and how the main observables (amplitude, phase coherence, non-Gaussianity) become consistency tests of the boundary→bulk mapping.

6. Chapter 6 — Isotropy, Gaussianity and Perturbations

When statistical structure replaces ad hoc initial conditions

6.1. Isotropy and Gaussianity as Observational Facts

An observational fact that is by now taken for granted: the Universe is isotropic and almost perfectly homogeneous on large scales. The cosmic microwave background (CMB) is uniform to one part in 10^5; the anisotropies are small, Gaussian, and well described by a nearly scale-invariant spectrum. In the standard model these facts require an entire ad hoc mechanism (inflation) to be reproduced. The question we address in this chapter is whether, in the holographic-entropic framework, the same facts emerge naturally rather than requiring an additional mechanism.

6.2. If Information Is on the Boundary, the Interior Cannot Be Arbitrary

Returning to the key idea, now with different eyes: the fundamental information of the Universe is encoded on a holographic surface. This surface contains an enormous number of degrees of freedom:

$$N \sim \frac{A}{\ell_P^2} \sim 10^{122}. \tag{7}$$

To grasp this number: 10^{122} is larger than the number of atoms in the observable universe ($\sim 10^{80}$), larger than the number of possible chess games ($\sim 10^{120}$), larger than any quantity encountered in ordinary physics. It represents, in a precise sense, the maximum information the cosmos can encode—the holographic capacity of the causal boundary.

The estimate $N \sim A/\ell_P^2$ is a *microscopic* count. The central-limit reasoning we use does *not* assume that all these degrees of freedom contribute as independent variables at cosmological resolution. Rather, the observable bulk fields are reconstructed only after coarse-graining on the screen, so what matters is an *effective* number $N_{\rm eff}$ of quasi-independent patches.

Equivalently, if correlations on the screen decay beyond a lateral scale $L_{\rm corr}$ (defined intrinsically on the screen), then the screen can be partitioned into patches of area $\sim L_{\rm corr}^2$, and one expects $N_{\rm eff} \sim A/L_{\rm corr}^2$ up to order-one factors that capture residual correlations. This is the sense in which $N_{\rm eff}$ is a mesoscopic multiplicity controlling the typical fluctuation level; below we estimate $L_{\rm corr}$ from physical processes rather than treating $N_{\rm eff}$ as a fit parameter.

A question naturally arises:

What type of statistical distribution emerges from the sum of an enormous number of independent or weakly correlated contributions?

The answer is one of the most robust laws of mathematics and physics:

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6.3. The Central Limit Theorem as "Final Guard"

The central limit theorem is not a technical detail: it is a law of statistical stability.

Figure 8. Central Limit Theorem applied to weakly correlated contributions. The sum of many such contributions converges to a Gaussian distribution; in the holographic framework, this provides a natural origin for the quasi-Gaussianity of CMB anisotropies, given a large $N_{\rm eff}$ of independent patches on the boundary. The CLT does not exclude small non-Gaussian deviations (see Sec. 6.13.4 for the discriminative $f_{\rm NL}$ test).

It says that, regardless of the microscopic distribution of contributions, the sum of many of them tends to a Gaussian distribution. In our framework, cosmological anisotropies are then not "mysterious initial imprints" but residual statistical fluctuations of a system with enormous boundary degrees of freedom: Gaussianity of the CMB is a natural output of the CLT, not an input.

Correlations. The CLT argument is invoked in its minimal form: it requires only that correlations among effective boundary patches decay sufficiently fast beyond a correlation scale $L_{\rm corr}$. Strong long-range correlations are not excluded; rather, they are pushed into controlled departures from Gaussianity (quantified by $f_{\rm NL}$) and into the low-ℓ sector where the framework expects anomalies to concentrate.

6.4. Isotropy: Not an Initial Condition, but a Consequence

In the standard model isotropy is fragile: a slight change of initial conditions makes the Universe chaotic. In the holographic-entropic framework the situation is reversed: isotropy is the most probable state of a system with information distributed on a surface. Not because "someone chose it," but because every internal direction is a statistical projection of a boundary lacking privileged directions. The boundary does not "know" what north or south is, and the interior inherits this ignorance as symmetry.

6.5. Perturbations: Small Because They Must Be

Here appears the "opposite paradox" compared to the standard scenario:

> *If the boundary has an enormous number of degrees of freedom, then by the central limit theorem the Universe should be* ***too*** *uniform. Why do we still observe $\delta\rho/\rho \sim 10^{-5}$?*

The answer is simple but not trivial: the central limit theorem (CLT) makes the **form** (Gaussian) robust, it does not automatically fix the **scale** of the amplitude. The amplitude depends on the effective number of statistically independent contributions that survive in the observable coarse-graining.

From N to $N_{\rm eff}$.

The holographic count $N \sim A/\ell_P^2 \sim 10^{122}$ is microstatistical. The cosmological observable, instead, is a "long" field reconstructed in the bulk: it inherits only an *effective* number $N_{\rm eff}$ of quasi-independent domains (or patches) on the screen.

A minimal model (not unique, but instructive) is this: a macroscopic order parameter X derives from the average of $N_{\rm eff}$ local contributions x_i,

$$X \equiv \frac{1}{N_{\rm eff}} \sum_{i=1}^{N_{\rm eff}} x_i, \qquad \mathrm{Var}(X) \simeq \frac{\mathrm{Var}(x)}{N_{\rm eff}} \quad \text{(approximate independence)}.$$

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If $\mathrm{Var}(x) \sim \mathcal{O}(1)$, then the typical fluctuation scales as

$$\sigma_X \sim \frac{1}{\sqrt{N_{\rm eff}}}. \tag{8}$$

This is the scaling we exploit below: a large $N_{\rm eff}$ produces small typical fluctuations (Eq. 8), which translates into the observed $\delta T/T \sim 10^{-5}$ once the boundary patch count is fixed.

Numerical sanity check (but not input).

In the holographic framework, the amplitude of scalar fluctuations is linked to the fact that the observable field in the bulk arises from a *mixing* (coarse-graining) of many quasi-independent contributions on the boundary. The order of magnitude of this "effective multiplicity" is therefore fixed by the number of statistically quasi-independent patches on the last scattering surface (LSS), which we denote $N_{\rm eff}$.

Lateral correlation scale $L_{\rm corr}$ and estimate of $N_{\rm eff}$.

we introduce a lateral correlation length on the boundary, $L_{\rm corr}$, which quantifies the typical (comoving) size of a quasi-independent patch. Then, at order of magnitude level,

$$N_{\rm eff} \sim \frac{4\pi R_{\rm LSS}^2}{L_{\rm corr}^2} \sim \left(\frac{R_{\rm LSS}}{L_{\rm corr}}\right)^2, \tag{9}$$

where $R_{\rm LSS}$ is the comoving radius of the LSS.

Physical derivation of the scale $L_{\rm corr}$.

The scale $L_{\rm corr}$ is not a free parameter to fit. The natural way to define it within this framework is operational: $L_{\rm corr}$ is the lateral scale below which boundary correlations are not preserved by the coarse-graining map that produces the observed bulk field. In other words, $L_{\rm corr}$ is fixed by the resolution at which the bulk effectively reconstructs the boundary statistics, not by an independent dynamical mechanism.

This operational definition has a useful consequence: it tells us where to look for $L_{\rm corr}$ in the observed cosmology. The Silk scale $\lambda_{\rm Silk}$ is precisely the bulk-side manifestation of this coarse-graining: it is the smallest scale at which acoustic information survives diffusive damping in the photon-baryon plasma. Information on scales $\ll \lambda_{\rm Silk}$ is erased before reaching the last-scattering surface and therefore does not appear in the observable, regardless of what was present on the boundary; information on scales $\gg \lambda_{\rm Silk}$ propagates coherently. The Silk scale is therefore the observational *readout* of the coarse-graining, not its origin.

Concretely, before recombination photons diffuse through the plasma with mean free path $\lambda_{\rm mfp} \sim 1/(n_e\sigma_T)$, so that the diffusion scale over a cosmic time t is

$$\lambda_D \sim \sqrt{c \cdot \lambda_{\rm mfp} \cdot t} \sim \sqrt{\frac{c \cdot t}{n_e \sigma_T}}.$$

At recombination ($t_{\rm rec} \sim 380\,000$ years, $z \sim 1100$) one obtains $\lambda_{\rm Silk} \sim 8$–12 Mpc (comoving). The identification

$$L_{\rm corr} \sim \lambda_{\rm Silk}/\alpha, \qquad \alpha \sim 3\text{–}10,$$

where α accounts for the fact that damping is not a sharp cutoff, gives $L_{\rm corr} \sim 1$–3 Mpc.

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The logical structure is therefore the inverse of what it may appear at first reading. The framework does not derive L_{corr} from the bulk and then use it to predict bulk amplitude (that would be circular). It uses an operational definition of L_{corr} on the boundary and notes that, if the framework is correct, the lateral scale extracted from plasma microphysics must coincide with this operational scale up to order-unity factors. The agreement is a *consistency requirement* that the framework imposes on cosmology, not a derivation from cosmology. The burden of explanation lies on the alternative: a critic who rejects the identification must explain why two distinct microscopic scales—one set by boundary coarse-graining, one set by photon diffusion—should coincide numerically across redshift.

It is often useful to rewrite the same relation in inverted form: the typical "areal dimension" of a patch is $A_{\text{patch}} \sim 4\pi R_{\text{LSS}}^2 / N_{\text{eff}}$, and therefore a characteristic lateral scale is

$$L_{\text{corr}} \sim \sqrt{A_{\text{patch}}} \sim R_{\text{LSS}} \sqrt{\frac{4\pi}{N_{\text{eff}}}}. \tag{10}$$

With $R_{\text{LSS}} \simeq 14\,\text{Gpc}$ (comoving) and $L_{\text{corr}} \sim 1$–$3\,\text{Mpc}$, we get $N_{\text{eff}} \sim (14000/2)^2 \sim 10^7$–$10^8$. Considering uncertainty on L_{corr} and geometric effects, the order of magnitude $N_{\text{eff}} \sim 10^7$–10^9 is robust, with the canonical value adopted throughout the rest of the paper being $N_{\text{eff}} \sim 10^8$. We use this canonical value in all subsequent estimates (A_s, $\delta T/T$, $f_{\text{NL}}^{\text{local}}$, n_s) unless otherwise noted.

Non-circularity: A_s as a consistency check.

Given N_{eff}, the expected order of magnitude for the scalar fluctuation amplitude is $A_s \sim 1/N_{\text{eff}}$ (see [7], Sec. 3.2 for derivation). With $N_{\text{eff}} \sim 10^8$, this gives $A_s \sim 10^{-9}$, in agreement with the observed amplitude $A_s \simeq 2 \times 10^{-9}$.

It is worth being clear about the logical status of this agreement. Because the lateral correlation scale L_{corr} is identified with the Silk scale, which is itself read off from the observed plasma physics, the agreement is a consistency test that the framework passes, not a parameter-free prediction. The Silk scale is the smallest scale that survives recombination in the standard plasma; in the present framework it must coincide, up to order-unity factors, with the lateral correlation scale of the boundary, and the numerical agreement confirms that it does. A genuine prediction would require computing L_{corr} from boundary dynamics independently of plasma physics—for instance from the spectral density $J(\omega)$ of Chapter 7—which is left to future work.

6.6. Primordial vs Transfer: What Remains Standard

A point of clarity (anti-referee): this work concerns the *origin* and *conceptual status* of initial conditions in the bulk, it does not replace plasma microphysics.

In other words:

- the **primordial sector** (origin of correlations and amplitude A_s) is reinterpreted as a property of the global state on the boundary;
- the **transfer** to the observed CMB (acoustic oscillations, Silk damping, recombination) remains described by standard physics (Boltzmann equations + recombination) once the primordial spectrum is fixed.

This is crucial: removing inflation as a "logical band-aid" does not mean giving up the part of cosmology that works best.

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6.7. Acoustic Peaks and Phase Coherence: A Reframing

A key observation (which a cosmologist referee will ask immediately): it is not enough to explain *how* small and Gaussian the anisotropies are; one must also preserve the **phase coherence** that produces the regular sequence of acoustic peaks in C_ℓ. In the inflationary framework, this coherence follows from the fact that adiabatic perturbations arise as a single quasi-classical mode with well-defined phase on super-horizon scales.

In our framework, we argue that this problem is re-framed rather than solved: if the CMB peaks are understood as **normal modes of the holographic boundary** rather than as oscillations with free phases, the coherence becomes a property of the modal structure, just as the frequencies of a drum are determined by its geometry. We are explicit that this is a change of language, not a quantitative reproduction of the peak structure (see Sec. 6.13).

This reframing is developed in Sec. 6.13, where we discuss:

- The CMB peaks as a possible reflection of boundary geometry ("boundary spectroscopy"), at the level of an interpretive proposal
- The amplitude $\delta T/T \sim 10^{-5}$ as emerging from $1/\sqrt{N_{\text{eff}}}$
- Low-ℓ anomalies acquiring a geometric meaning

Phase coherence: a reframing, not a solution

The standard framing asks: "why are the phases of acoustic oscillations aligned?" This presupposes that phases are free variables.
In the holographic framing, the peaks are normal modes of the boundary—characteristic frequencies determined by structure, for which coherence is a property of the modal structure rather than a separately tuned condition. This reframes the question; it does not, in this paper, reproduce the observed peak positions and heights, which would require an explicit boundary model and transfer calculation (deferred to future work).

6.8. Near Scale-Invariance and Tilt: What to Expect

In the standard model with inflation the primordial spectrum is nearly scale-invariant but not exactly: $n_s \neq 1$, with slow-roll parameters fixing the tilt.

In the present framework, near scale-invariance is expected as a natural property of a boundary state that is near a conformal (or quasi-conformal) symmetry over a wide range. The heuristic is the following. A conformal boundary has no intrinsic length scale: correlators are scale-invariant, and the bulk reconstruction inherits scale invariance up to the resolution scale of the coarse-graining. The observed deviation $n_s = 0.965 \pm 0.004$, slightly red-tilted, then admits a natural interpretation: the boundary is not exactly conformal but close to it, with the breaking of scale invariance set by the same finite-N_{eff} structure that produces the perturbation amplitude. In particular, an effective spectral exponent

$$n_s - 1 \;\sim\; -\frac{c_1}{\log N_{\text{eff}}}$$

with $c_1 = \mathcal{O}(1)$ would give $n_s - 1 \sim -0.05$ for $N_{\text{eff}} \sim 10^8$, of the correct order. The derivation of c_1 from boundary dynamics requires the kernel formalism of Chapter 7 and is deferred to the companion paper [7]; what we record here is that the observed value is structurally consistent with the framework, not a free parameter to be fitted.

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A confirmed observation of n_s significantly different from ~ 0.95–0.97, or of strong scale dependence (large running α_s), would be in tension with the near-conformal boundary picture.

6.9. CMB aNomalies: From Nuisance to Clue

Figure 9. CMB temperature power spectrum, with the low-multipole regime highlighted. The observed tensions and anomalies (power suppression, alignments) appear in the range $\ell \lesssim 30$. A finite informational boundary can produce suppressions or non-local correlations at the largest angles; the quantitative expectation is a suppression factor in the range 0.7–0.9 relative to standard ΛCDM (Sec. 6.13.5).

The anomalies observed in the CMB—alignments at low multipoles, lack of power at large angles, possible non-local correlations—have been extensively documented by the Planck collaboration [38,39]. Their statistical significance remains debated (typically 2–3σ), and they could be statistical flukes. However, they persist across data releases and analysis methods.

In the holographic-entropic framework, they acquire potential physical meaning. When the system is finite, information is limited, and the boundary imposes a natural IR cutoff, deviations from statistical homogeneity at the largest scales are not anomalies—they are *expected signatures* of boundary geometry.

The Universe is not infinite in an informational sense. This must be reflected on the largest observable scales. Sec. 6.13 develops this interpretation in detail.

6.10. Primordial Gravitational Waves: A Strong Prediction

In the standard inflationary framework, tensor modes (primordial gravitational waves) are generated by quantum fluctuations during inflation.

In the holographic framework without inflation, the mechanism for generating primordial tensor modes is absent.

Therefore:

- The framework predicts $r < 10^{-3}$ (only secondary sources).
- A detection of $r > 10^{-2}$ with confirmed primordial origin would require new physics.

Benchmark caution. In the minimal (non-inflationary) holographic setting, the expectation is that *primordial* tensor modes are parametrically suppressed, i.e. effectively $r \simeq 0$ up to small boundary-sourced residuals. The quoted benchmark $r \lesssim 10^{-3}$ should be read as a conservative target scale rather than a sharp derivation; a confirmed primordial detection at $r \gtrsim 10^{-2}$ would falsify the minimal framework and require an additional tensor-generating sector.

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6.11. Quantitative Comparison with Observations

Table 4. Quantitative comparison with observations. Status: ✓ = consistent, ∼ = order-of-magnitude match, — = not derived in this paper.

Observable	Measured value	Framework prediction	Status
A_s (scalar amplitude)	2.1×10^{-9}	$\sim 1/N_{\text{eff}} \sim 10^{-9}$	✓
n_s (spectral index)	0.965 ± 0.004	$n_s - 1 \sim -c_1/\log N_{\text{eff}}$, heuristic (Sec. 6.8)	✓
r (tensor-to-scalar)	< 0.036 (95% CL)	$< 10^{-3}$	✓
$f_{\text{NL}}^{\text{local}}$	-0.9 ± 5.1	$\lesssim 1$–5 (from CLT)	✓
Gaussianity	High ($< 10^{-5}$ dev.)	Natural from CLT	✓
Phase coherence	Acoustic peaks	Reframed (Sec. 6.13)	∼
Low-ℓ anomalies	2–3σ tensions	Expected from finite boundary	∼

6.12. Falsifiability: Predictions and Killer Tests

KILLER PREDICTION

If spacetime is emergent (not fundamental), there is no primordial mechanism to generate gravitational waves from quantum fluctuations of the metric tensor. The framework predicts:

$$\boxed{r < 10^{-3}}$$

where r is the tensor-to-scalar ratio.

Falsification: A robust measurement of $r > 10^{-2}$ with primordial origin (not foreground, not lensing) would **falsify** the minimal version of the framework and require an inflationary mechanism (or equivalent).

Timeline: LiteBIRD [24] (launch ∼2028) will reach sensitivity $\sigma(r) \sim 10^{-3}$.

Complete falsifiability checklist

Here we do not write poetry: we explicitly list *what* is tested and *what* fails if the test fails.

Killer tests (if they occur, the minimal "screen-dominated" version dies):

- **Primordial tensors (CMB B-modes):** a robust measurement of

$$r \gtrsim 10^{-2}$$

with spectrum compatible with primordial origin (not foreground / not lensing-residual) would make it *extremely* difficult to sustain that spacetime is only an IR emergence *without* additional dynamics capable of generating tensors (inflation or equivalent mechanism on boundary).
Quantitative prediction: the framework naturally predicts $r \lesssim 10^{-3}$–10^{-4}, since the absence of a dynamical inflationary mechanism does not generate primordial gravitational waves from slow-roll. A heuristic scaling supports this: in the absence of a bulk-side tensor-sourcing mechanism analogous to the energy-momentum tensor in AdS/CFT, residual boundary-sourced tensors are expected to be suppressed by at least a factor $(H/M_P)^2$ relative to scalar fluctuations, which at CMB scales corresponds to $r \lesssim 10^{-10}$. The bound $r \lesssim 10^{-3}$ adopted as the falsifiability threshold is therefore a conservative upper benchmark, not a sharp derivation. Current bound (Planck+BICEP/Keck 2021) is $r < 0.036$ [22] at 95% CL; future experiments (LiteBIRD, CMB-S4) will reach sensitivity $\sigma(r) \sim 10^{-3}$.
- **Large "local-type" non-Gaussianity:** a robust measurement of

$$|f_{\rm NL}^{\rm local}| \gg \mathcal{O}(1)$$

is incompatible with an origin based on mixing/CLT and coarse-graining, unless extra structure is introduced (new degrees of freedom, multi-fields, or a memory kernel with strong non-linearity).
Quantitative prediction: with the canonical $N_{\rm eff} \sim 10^8$ adopted in Sec. 6.5, the CLT implies $|f_{\rm NL}^{\rm local}| \lesssim 1$–$5$, compatible with Planck limits ($f_{\rm NL}^{\rm local} = -0.9 \pm 5.1$). A measurement of $|f_{\rm NL}| > 10$ with high significance would falsify the minimal version.
Shape dependence (discriminative). In a CLT-pure origin the dominant non-Gaussian signal is of *local type*, generated by point-wise nonlinearity in the boundary-to-bulk reconstruction. An *equilateral* contribution would require derivative-type interactions among neighbouring boundary patches and is expected to be subdominant in the minimal framework. An *orthogonal* contribution is more exotic and would not arise naturally from coarse-graining alone. A future detection in which equilateral or orthogonal contributions dominate over local would therefore not falsify the framework as such, but would indicate that the minimal CLT-based picture is incomplete and requires an explicit boundary-dynamics extension.

Consistency tests (not free: the framework must reproduce them):

- **Acoustic peaks and phase coherence:** the observed phase coherence of peaks in the CMB power spectrum requires that effective initial conditions in the bulk be *globally coherent* and not a patchwork of random phases. In our framework this becomes a direct constraint on the "boundary $\to$ bulk" map and on degrees of freedom that survive coarse-graining.
- **Standard transfer:** plasma physics (acoustic oscillations, Silk damping, LSS thickness) remains standard. Our mechanism intervenes on initial conditions and primordial statistics, not on post-initial Boltzmann calculation.

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Complete falsifiability checklist

Signals that strengthen the framework:

- increasingly stringent limits on r (tending to $r \to 0$) and absence of observable primordial tensors;
- high Gaussianity with weak non-Gaussianity compatible with mixing/coarse-graining;
- persistence (with increasing significance) of low-ℓ anomalies consistent with "global" (boundary/state) origin, rather than pure statistical noise.

Note of caution: this work argues that inflation is not *logically necessary* for isotropy/Gaussianity in a holographic framework; it does not claim to prove that inflation is false in absolute terms.

6.13. Phase Coherence and the CMB: A Reframing

The acoustic peaks of the CMB present what is often called the "phase coherence problem": perturbations at vastly different scales appear to oscillate in phase, producing the sharp peaks observed at $\ell \sim 220, 540, 810, \ldots$ rather than a featureless spectrum. The standard resolution invokes inflation: all modes exit the horizon with the same phase (the Bunch-Davies vacuum), and this phase is preserved until recombination.

In the holographic-entropic framework, this problem is re-framed rather than solved in detail: what looks like a fine-tuned alignment of phases becomes a property of the modal structure of the boundary. We are careful not to overstate this. The reframing changes the language in which the question is posed; it does not, in this paper, reproduce the quantitative structure of the peaks.

6.13.1. From Oscillations to Normal Modes

The standard picture treats the CMB peaks as frozen snapshots of acoustic oscillations in the photon-baryon plasma. The "phases" of these oscillations are free parameters that happen to be aligned.

The holographic reframing is different. If the CMB anisotropies reflect the structure of the holographic boundary—specifically, the normal modes of the boundary's entropic "foam"—then the alignment is not of free phases but of characteristic frequencies of the boundary, determined by its geometry, just as the frequencies of a drum are determined by its shape.

Asking "why are the phases coherent?" is then closer to asking "why are the frequencies of a drum coherent?"—the coherence is a property of the structure, not a separately tuned condition. We stress, however, that this is a conceptual reframing, not a derivation: showing that the boundary normal modes reproduce the *observed* peak structure—the positions $\ell \sim 220, 540, 810$, the ratio $\ell_2/\ell_1 \approx 2.45$, the baryon-loading asymmetry between odd and even peaks, and Silk damping—would require an explicit boundary model and a full transfer calculation, which is beyond the scope of this foundational paper. What we claim here is only that the framework offers a natural language for the coherence; the quantitative reproduction is deferred.

This reframing has precedent. Oaknin [40] showed that CMB peaks can emerge from causal boundary conditions without inflation: a compact, causally connected region naturally produces a discrete (harmonic) spectrum, with modes at $k_n = n\pi/H_{\rm eq}^{-1}$. Independently, the proposal of a bounded, spherical cosmological region with a physical boundary has been developed quantitatively by Gaztañaga [33]; although that "Black Hole Universe" model reaches a conclusion this paper argues against on causal grounds (Chapter 3), it demonstrates that the idea of a finite cosmological cavity with boundary-determined structure can be made quantitative and is not without precedent in the recent literature.

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6.13.2. The Amplitude: From Fine-Tuning to Statistics

The observed amplitude $\delta T/T \sim 10^{-5}$ is, in standard cosmology, determined by the inflaton potential—a free parameter requiring fine-tuning to match observations.

In the holographic framework, this amplitude emerges from statistical mechanics. If the boundary consists of N_{eff} effective degrees of freedom (cells, patches, or entropon clusters), the central limit theorem gives:

$$\frac{\delta T}{T} \sim \frac{1}{\sqrt{N_{\text{eff}}}}. \tag{11}$$

From Sec. 6.3, we estimated $N_{\text{eff}} \sim (R_p/L_{\text{corr}})^2 \sim 10^7$–$10^9$ (canonical value $\sim 10^8$; Sec. 6.5), where $L_{\text{corr}} \sim \lambda_{\text{Silk}}$ is the correlation scale. This yields $\delta T/T \sim 10^{-4}$ to 10^{-5}, consistent with observations.

This is not a first-principles derivation: L_{corr} has not been derived from boundary microphysics independently of plasma physics. But the *mechanism* is robust: the smallness of CMB anisotropies reflects the large number of boundary degrees of freedom, not fine-tuning of a potential.

6.13.3. The Peaks as Boundary Spectroscopy

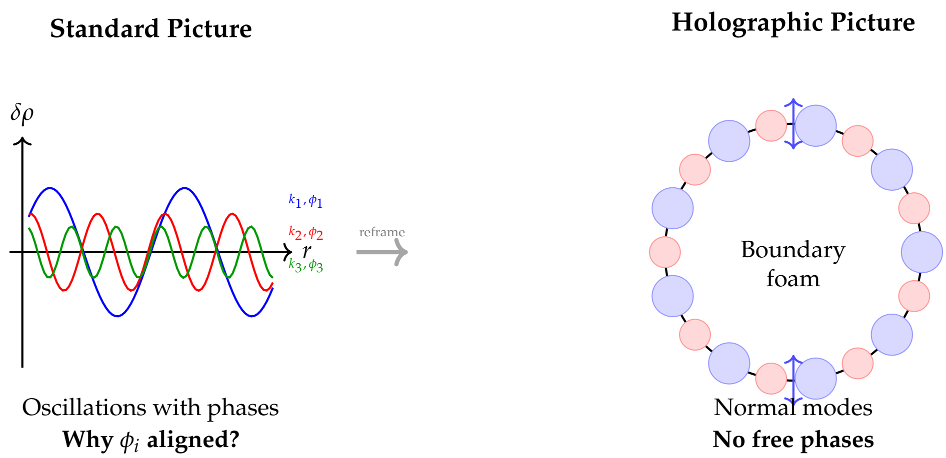

Figure 10. Two pictures of CMB peaks. **Left**: Standard view—acoustic oscillations with phases ϕ_i that require explanation for their alignment. **Right**: Holographic view—normal modes of the boundary structure. There are no free phases; the "peaks" are characteristic frequencies determined by geometry.

The position of the first peak ($\ell_1 \sim 220$) corresponds, naively, to a characteristic angular scale on the boundary. Translating multipole to physical scale via the comoving distance to last scattering gives, by dimensional argument,

$$L_{\text{cell}} \sim \frac{R_{\text{boundary}}}{\ell_1} \sim \frac{14\,\text{Gpc}}{220} \sim 60\text{–}150\ \text{Mpc}, \tag{12}$$

which is the same order of magnitude as the baryon acoustic oscillation (BAO) sound horizon $r_s \sim 147$ Mpc [21,41]. We do not claim that this is more than a numerical agreement at the current level of treatment. The standard derivation of the sound horizon from plasma physics is precise and quantitatively successful; the present framework offers an alternative *interpretation* of the same number—in the boundary language, r_s would acquire the meaning of a characteristic cell scale on the screen—but without an independent dynamical derivation it remains an interpretive proposal rather than a competing prediction. The agreement of orders of magnitude is encouraging; a genuine test would require deriving r_s from

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boundary microphysics independently of plasma dynamics, which is beyond the scope of the present argument.

The ratios between peaks ($\ell_2/\ell_1 \approx 2.45$, $\ell_3/\ell_1 \approx 3.68$) deviate from simple harmonics. In standard cosmology, this encodes the baryon-to-photon ratio through the modulation of compressional and rarefaction peaks; this is a quantitative success of standard physics. In the holographic framework, the same deviations from harmonic spacing *could* encode anharmonic structure of the boundary, but this is at present an interpretive translation, not a numerical prediction. We record it here as a direction for future quantitative work rather than as a current claim.

6.13.4. The Texture: Seeing the Boundary

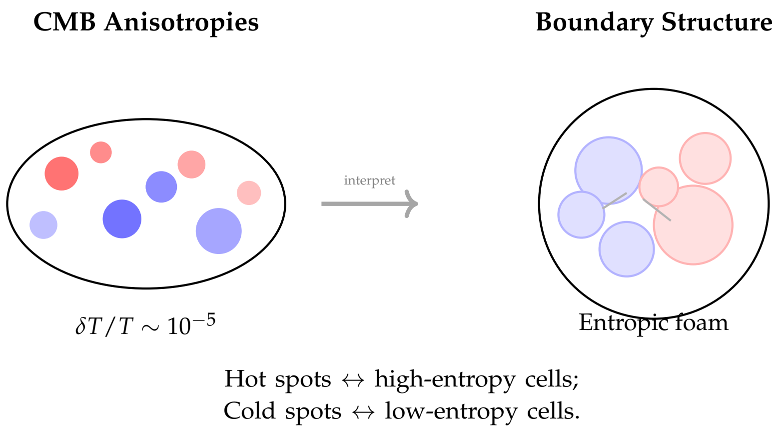

Figure 11. The CMB as a photograph of the holographic boundary. **Left**: The observed CMB anisotropy pattern with hot (red) and cold (blue) spots. **Right**: Interpretation as the intrinsic "foam" structure of the holographic boundary. The spots are not perturbations on a smooth background; they *are* the structure—the texture of the entropic surface from which spacetime emerges.

We propose that the CMB anisotropy pattern is not merely a record of bulk perturbations at recombination. It is a *photograph of the holographic boundary*—its intrinsic texture, its "bubbliness."

Each hot spot corresponds to a region of the boundary with locally higher entropy; each cold spot to a region with lower entropy. The pattern is not "the universe at 380,000 years" but the *shape of the holographic screen* from which spacetime emerges.

The amplitude $\delta T/T \sim 10^{-5}$ is then not a measure of how "perturbed" the early universe was. It is a measure of the *granularity* of the boundary—how much its entropy density varies from cell to cell. This granularity is fixed by the number of cells: $\delta T/T \sim 1/\sqrt{N_{\text{eff}}}$.

6.13.5. Low-ℓ Anomalies: Boundary Geometry

The observed anomalies at low multipoles—power deficit at $\ell < 30$, quadrupole-octupole alignment—have been extensively documented [38,39]. Their statistical significance (2–3σ) leaves room for debate: they could be statistical flukes.

In the holographic framework, however, these anomalies may carry geometric information:

- **Power deficit at low ℓ**: The boundary is finite. The largest-scale modes (lowest ℓ) "feel" this finiteness and are suppressed—analogous to finite-size effects in condensed matter.

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- **Axis alignments**: The boundary may not be perfectly spherical. A slight ellipsoidal deformation would produce preferred directions in the low-ℓ modes.

Expected range of suppression.

A finite causal screen of areal radius R_p imposes an IR cutoff on the spatial spectrum at $\ell_{\rm IR} \sim 1$, with the suppression of power building up smoothly over a window $\Delta\ell \sim \mathcal{O}(10)$. Dimensional arguments combined with the finite-volume corrections familiar from condensed-matter analogues suggest a suppression factor in the range 0.7–0.9 relative to the standard ΛCDM prediction in the lowest decade of multipoles, decaying to unity by $\ell \sim 30$. This is consistent in order of magnitude with the observed $\sim 10\%$ deficit at $\ell < 30$ [39]; a deficit much smaller than $\sim 5\%$ or much larger than $\sim 30\%$ would be in tension with the framework. The quantitative prediction requires specifying the boundary geometry and the coarse-graining map, and is developed in the companion paper [7]; the present statement is a structural expectation, not a fit.

These interpretations are tentative but offer a *physical explanation* where the standard model offers none.

6.13.6. What This Framework Claims and Does Not Claim

It claims:

- The phase coherence problem is *reframed* in the holographic interpretation: coherence becomes a property of boundary modal structure (quantitative reproduction deferred).
- The CMB amplitude $\delta T/T \sim 10^{-5}$ *emerges* from boundary statistics via CLT.
- The peaks encode boundary geometry—this is a *reinterpretation* of known physics.
- Low-ℓ anomalies may have *geometric meaning* related to boundary shape.

It does not claim:

- A complete quantitative derivation of the CMB spectrum from boundary geometry.
- Numerical predictions that differ from standard cosmology (at present).
- Proof that this interpretation is correct.

6.13.7. The Consistency Test

The framework makes a strong *consistency requirement*: the parameters describing boundary structure ($\rho(\mu^2)$, α, $L_{\rm corr}$) must simultaneously fit:

1. The CMB power spectrum (peak positions, amplitudes, damping)
2. Galactic rotation curves (where the same $\rho(\mu^2)$ produces logarithmic tails [7])
3. Dark energy dynamics ($w(z) \approx -1 + 2\alpha/3$)

The framework makes a strong consistency requirement: a single parameter set must fit the CMB power spectrum (peak positions, amplitudes, damping), galactic rotation curves (where the same $\rho(\mu^2)$ produces logarithmic tails [7]), and dark energy dynamics ($w(z) \approx -1 + 2\alpha/3$). If such a global fit succeeds, the unification provides powerful evidence; if different parameters are required for each channel, the framework fails as a unified theory. This global fit—which can be called *holographic spectroscopy*—is the natural next step beyond the present paper.

6.14. Bridge to Chapter 7: Foundational Results So Far

The foundational part can be closed here. Three points are now in place:

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- the “horizon problem” arises when one presumes that bulk initial conditions are free and local; in a holographic framework, global coherence is a property of the state on the boundary;
- the CLT makes the **Gaussianity** of anisotropies natural, but does not force an infinitesimal amplitude: amplitude is controlled by an effective number N_{eff} (Eq. 9) and a correlation scale ℓ_{corr} (Eq. 10);
- inflation passes from logical necessity to contingent possibility: it is no longer the only way to obtain a nearly isotropic and nearly Gaussian CMB.

7. Chapter 7 — Entropic Hysteresis

Memory, non-Markovianity, and effective dynamics

Note on temporal variables. Throughout this chapter the parameter t refers to the geometric (FRW) coordinate time, and integrals such as $\int dt'$ are computed against this geometric label. The physically meaningful evolution variable in the framework developed in Chapter 5 is the entropic time $\tau_S(t)$ of Eq. (3), which is a monotone reparametrization of t for $w_{\text{eff}} > -1$. The two descriptions are equivalent and the kernel K_R can be expressed in either parameter; we use t here for notational continuity with the open-system literature [42,43]. The dynamical content of this chapter does not depend on the choice of parameter.

Scope and aim of this chapter. The goal here is not to derive the full hysteretic dynamics of the holographic boundary—that derivation, with explicit kernels and quantitative fits, is the content of the companion paper [7]. The aim of the present chapter is more limited and more structural: to show that, *given* the necessity of a boundary description established in Chapters 2–4, the bulk dynamics inherits a definite qualitative form—an open-system Langevin equation with a non-Markovian memory kernel—whose memory regime is constrained by the near-saturation property of Theorem 1. In other words, the chapter argues that entropic hysteresis is not an additional postulate but a structural consequence of the framework.

7.1. The Bulk as an Open Quantum System

In the holographic picture established in Chapter 4, the bulk degrees of freedom we observe are not fundamental: they are reconstructed from the screen via coarse-graining. Whenever a fundamental description is reconstructed from a subset of its degrees of freedom by integrating out the rest, the reduced description acquires the structure of an open quantum system: a system coupled to a bath, where the bath consists of the integrated-out degrees of freedom. In the present context:

- the “system” is the bulk field content accessible to the observer;
- the “bath” is the set of boundary degrees of freedom whose collective state determines the reconstruction;
- the dynamics of the system is obtained by tracing out the bath, producing dissipation, noise and memory in the reduced description.

The framework of open quantum systems in field theory and cosmology is mature and has been developed extensively by Calzetta and Hu [44] and by Boyanovsky [45]; we use it here in the qualitative form that the necessity argument requires.

7.2. The Schwinger–Keldysh Formalism

The appropriate field-theoretic formalism for open-system dynamics is the Schwinger–Keldysh closed-time-path (CTP) approach [42,43], which describes the evolution of expectation values rather than S-matrix elements and is therefore suited to non-equilibrium and time-asymmetric situations. Applied to a bulk field ϕ coupled to the boundary degrees of freedom and integrating out the latter, the CTP procedure yields an

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effective action whose imaginary part encodes dissipation and noise, with the Feynman–Vernon influence functional [46] as the prototypical example. The structural output, valid under standard assumptions (linear coupling, Gaussian bath response), is a generalized Langevin equation for the surviving bulk variable.

7.3. The Memory Kernel

The reduced equation of motion for a bulk variable $\phi(t)$ takes the form

$$\ddot{\phi}(t) + V'(\phi) + \int_{-\infty}^{t} K_R(t-t')\,\dot{\phi}(t')\,dt' \;=\; \xi(t), \tag{13}$$

where $K_R(\tau)$ is the retarded memory kernel built from the symmetric and anti-symmetric two-point correlators of the boundary operators, and $\xi(t)$ is a stochastic noise satisfying a fluctuation–dissipation relation with K_R. The structure of K_R is determined entirely by the spectral density of the boundary,

$$J(\omega) \;=\; \frac{1}{\pi}\sum_n |c_n|^2\,\delta(\omega-\omega_n), \tag{14}$$

which encodes how boundary modes of frequency ω couple to the bulk field. The low-frequency behaviour of $J(\omega)$ controls the long-time tail of $K_R(\tau)$ and therefore determines whether the dynamics is Markovian or carries memory.

7.4. Why the Cosmological Boundary Is Near-Critical

The crucial point of this chapter is that the spectral character of the boundary is not free: it is constrained by the cosmological setting established in Chapters 2–3. The argument runs as follows.

A bath with a well-defined infrared cutoff ω_{IR} produces memory effects that decay exponentially on the timescale $1/\omega_{\mathrm{IR}}$. For the cosmological boundary, the relevant IR cutoff is set by the inverse particle-horizon time, $\omega_{\mathrm{IR}} \sim c/R_p$. However, Theorem 1 implies $R_p/R_g \leq 1$ with the ratio close to unity over significant fractions of cosmic history. The near-saturation means that there is *no parametrically large separation* between the gravitational scale and the causal scale: the bath does not possess a hierarchy of frequencies between which to organize a clean Markovian limit. In the language of open quantum systems, this is the structural signature of a critical or near-critical environment: a spectral density that behaves as $J(\omega) \sim \omega^{\nu}$ for small ω, with $\nu \to 0$, rather than as $J(\omega) \sim \omega$ (Ohmic) or $J(\omega) \sim \omega\,\Theta(\omega-\omega_{\mathrm{IR}})$ (gapped). The cosmological boundary is therefore expected to be sub-Ohmic or near-critical, with ν small.

This is not introduced as an independent postulate: it is the behaviour expected if the boundary sits near a quantum critical point, an expectation that the absence of a parametrically large frequency gap—itself a consequence of the near-saturation $R_p \sim R_g$ derived in Theorem 1—makes natural. We state it as a physically motivated expectation rather than as a theorem; the rigorous derivation requires the explicit construction of the boundary theory and is deferred to the companion work [7].

Concreteness via a toy model.

It is instructive to anchor the qualitative claim with a concrete construction. Consider a free 1+1-dimensional conformal field theory at the critical point—the prototype is a free massless boson with central charge $c = 1$, but the argument is generic for any unitary 2D CFT at criticality. The spectral density of a primary operator $\mathcal{O}$ of conformal dimension Δ in such a theory scales as $J_{\mathcal{O}}(\omega) \propto \omega^{2\Delta-1}$ at low frequency. For a marginal operator ($\Delta = 1$) this gives Ohmic behaviour; for a relevant operator ($\Delta < 1$)

one obtains $J(\omega) \propto \omega^{2\Delta-1}$ with exponent in $(-1,1)$, which is sub-Ohmic for $\Delta < 1$ and tends to the strictly flat (critical) limit as $\Delta \to 1/2$. The cosmological boundary that the present framework requires need not be a 2D free boson, but the structural lesson generalises: at criticality the dimension spectrum is dense and contains operators with arbitrarily small effective IR exponent, producing the near-critical spectral density $J(\omega) \sim \omega^{\nu}$ with $\nu \to 0$ that the argument of Sec. 7.4 predicts.

7.5. Memory Regimes and Observational Signatures

The qualitative consequences of the boundary spectral behaviour are summarized in Table 5.

Table 5. Memory regimes parametrized by the boundary spectral density. The near-saturation of $R_p \sim R_g$ established in Theorem 1 places the cosmological boundary in the sub-Ohmic to critical regime.

Regime	$J(\omega)$ for small ω	$K_R(\tau)$ at large τ
Markovian (gapped)	$\propto \delta(\omega - \omega_0)$	exponential decay, instantaneous in the limit
Ohmic	$\propto \omega$	$\propto \tau^{-2}$, short memory
Sub-Ohmic ($\nu < 1$)	$\propto \omega^{\nu}$	$\propto \tau^{-(1+\nu)}$, long memory
Critical ($\nu \to 0$)	approximately constant	$\propto \tau^{-1}$, maximal memory

A near-critical boundary produces three families of observable signatures that the framework can in principle be tested against:

- *Cosmological scale.* A power-law memory in K_R contributes a slowly decaying correction to the effective equation of state $w(z)$, with deviations from $w = -1$ scaling as a power of $\log(1+z)$ rather than as $(1+z)^{3(1+w_0)}$. This is the regime that the companion paper [7] fits against late-time cosmological data.
- *Galactic scale.* The same kernel applied to galactic-scale dynamics produces a memory-of-baryons effect: rotation curves carry a hysteretic signature correlated with the local baryonic history, distinct from the stochastic-feedback prediction of standard CDM. This is the prediction tested against the SPARC database in [7].
- *Laboratory scale.* A modulated Casimir experiment can probe the high-frequency response of the same kernel, providing an independent test on a completely different scale [8].

The structural prediction common to all three scales is that the same dimensionless parameter set should describe the kernel in all of them; the framework fails as a unified theory if this is not the case.

7.6. What This Chapter Establishes and What Is Delegated

The argument of this chapter establishes that:

1. Given the necessity of a boundary description (Chapters 2–4), the effective bulk dynamics has the form of a generalized Langevin equation with a non-Markovian kernel (Eq. 13).
2. Given the near-saturation property of Theorem 1, the kernel is in the sub-Ohmic to near-critical regime (Sec. 7.4).
3. The resulting memory effects produce signatures that connect cosmological, galactic and laboratory observations through a shared parameter set.

What is delegated to the companion paper [7] is the explicit construction of K_R from boundary micro-physics, the quantitative fit to SPARC, the parametrization of $w(z)$ corrections, and the operational link to

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the Casimir protocol. The present chapter aims only to show that entropic hysteresis is a structural feature, not an additional assumption.

8. Chapter 8 — Conclusions

8.1. Summary Without Rhetoric (but Without Timidity)

Summary of what has been demonstrated:

1. **Gravitational constraint (Theorem 1):** The observable Universe always satisfies $R_p \leq R_g$. This is not a coincidence but an algebraic identity valid in all cosmic epochs.
2. **Causal no-go (Theorem 2):** This constraint does not imply that we are inside a black hole. The causal structure of FRW is incompatible with a black hole interior.
3. **Holographic necessity:** After excluding all alternatives (volumetric description, modified gravity, cosmic coincidence, coordinate artifacts), the only coherent option is that fundamental information resides on a boundary, not in the volume.
4. **Entropic time:** If the bulk is emergent, time cannot be fundamental. It is a monotonic variable that tracks the accumulation of entropy on the screen.
5. **Observable consequences:** Isotropy, Gaussianity, and small perturbations emerge naturally from the central limit theorem applied to screen degrees of freedom. The absence of primordial tensor modes ($r < 10^{-3}$) is a falsifiable prediction.

A comment is in order on primordial tensor modes. In the minimal holographic-emergent scenario discussed here, there is no independent bulk amplification mechanism that generically sources a sizeable primordial tensor background. Accordingly, the natural expectation is a strongly suppressed tensor-to-scalar ratio, $r \lesssim 10^{-3}$ at CMB scales.

This statement should be read as a *minimal* prediction of the framework, not as a claim that tensor modes are impossible in principle. A robust detection at $r \gtrsim 10^{-3}$ would not falsify the necessity argument of this paper (rooted in causal/gravitational accounting), but it would indicate that an additional ingredient—such as an inflationary phase or another dedicated tensor-sourcing mechanism—must be present on top of the emergent/holographic reconstruction.

8.2. Declared Scope (Reminder)

As stated in the "Scope and limits" section at the beginning of this paper: we claim a *necessity argument*, not a complete theory. The framework shows that holographic description is required; it does not yet provide a complete model of boundary dynamics. The companion work [7] develops the dynamical mechanism, and [8] proposes a laboratory test.

8.3. Comparative Table: Standard Inflation vs Entropic-Holographic Framework

Table 6. Comparison of frameworks. The holographic-entropic framework reproduces key observables without requiring an inflationary mechanism.

Feature	Standard Inflation	Holographic-Entropic
Isotropy	Requires inflaton + fine-tuning	Emergent from screen democracy
Gaussianity	Quantum vacuum fluctuations	CLT from $N_{\rm eff}$ patches
$A_s \sim 10^{-9}$	From slow-roll parameters	From $N_{\rm eff} \sim 10^8$
$n_s \approx 0.965$	Slow-roll prediction	Heuristic: $n_s - 1 \sim -c_1/\log N_{\rm eff}$ (Sec. 6.8)
r (tensor modes)	$r \sim 0.001$–0.1 typical	$r < 10^{-3}$ (no mechanism)
Arrow of time	External assumption	Emergent from $dS/dt > 0$

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8.4. Parsimony: Counting the Assumptions

The comparison above concerns observables. A second comparison concerns the assumptions each framework must posit to reproduce those observables. This is the relevant axis for a parsimony argument: not which framework fits the data (both can be made to), but which one introduces fewer independent postulates beyond standard cosmology. Table 7 makes this count explicit.

Table 7. Postulate count beyond standard FRW cosmology and general relativity. The inflationary explanation of isotropy, Gaussianity and small perturbations requires six additional ingredients; the holographic-entropic explanation of the same observables requires one, and that one is itself motivated by an existing theorem (the covariant entropy bound) rather than introduced by hand. This is the precise sense in which the framework is more parsimonious: it is the application of Occam's razor to the same observational data.

Standard inflationary cosmology posits	**Holographic-entropic framework posits**
A new scalar field (the inflaton), not part of the Standard Model	No new field
A specific inflaton potential $V(\phi)$, chosen to match observations	No potential to specify
Slow-roll conditions on $V(\phi)$ (flatness, smallness of ϵ, η)	No slow-roll conditions
A Bunch–Davies initial vacuum state for the fluctuations	No special vacuum prescription
Initial conditions allowing inflation to start (itself debated)	No special pre-inflationary initial conditions
A graceful-exit / reheating mechanism connecting to the hot Big Bang	No reheating sector
Beyond standard FRW + GR: six additional ingredients	*Beyond standard FRW + GR: one ingredient — that information is encoded on the causal boundary, which itself follows from the covariant entropy bound*

Two clarifications keep this comparison honest. First, parsimony is a criterion for theory *choice* under empirical equivalence; it is not a proof that inflation is wrong. If a future observation requires a mechanism that only inflation provides (for instance, primordial tensor modes at $r \gtrsim 10^{-2}$), the postulate count is no longer the deciding factor and inflation is reinstated on empirical grounds. Second, the single ingredient on the right—boundary encoding of information—is motivated, not derived with mathematical force: as stated in the epistemic note of Sec. 4.3, the argument is strongly motivated within the adopted assumptions, not a theorem about nature. With those two caveats, the count stands: explaining the same observables, the holographic-entropic route adds fewer independent assumptions to standard cosmology than the inflationary route does.

8.5. Inflation: From Necessity to Possibility

The position of this work on inflation can be stated in one sentence: *within the assumptions adopted here, inflation moves from logical necessity to an optional dynamical mechanism*. The framework does not claim that inflation is false; it claims that the standard cosmological observables that motivated it—isotropy, near-Gaussianity, near-scale-invariance, the smallness of perturbations—can also be produced by the boundary statistics described in Chapter 6. Specifically:

- Isotropy on large scales follows from the absence of privileged directions on the screen.
- The Gaussian shape of the anisotropy distribution follows from the central limit theorem applied to N_{eff} quasi-independent patches.
- The amplitude $\delta T/T \sim 10^{-5}$ follows, at the level of order of magnitude, from $1/\sqrt{N_{\text{eff}}}$ with the canonical $N_{\text{eff}} \sim 10^8$ (Sec. 6.5).
- The phase coherence of the acoustic peaks is reinterpreted, in this framework, as a property of normal modes of the boundary rather than as a coordinated phase of independent oscillators (Sec. 6.13).

Inflation remains an internally consistent alternative for producing the same observables, and may be required if certain signatures appear: primordial tensor modes at $r \gtrsim 10^{-2}$, large equilateral non-Gaussianity, or other features that cannot be accounted for by boundary statistics alone. The framework does not place inflation on trial; it removes the logical necessity of invoking it as the default explanation. The two pictures should be regarded as competing models with overlapping predictions in their respective regions of parameter space, distinguishable by the falsifiable signatures listed in Sec. 6.12.

8.6. The Place of the Entropic-Hysteretic Paradigm

This work is part of a broader research program organized as Necessity → Mechanism → Laboratory anchoring:

1. **This paper (Foundation):** establishes *why* holographic description is necessary.
2. **Entropic Hysteresis [7]:** develops *how* the mechanism works (Schwinger-Keldysh derivation, quantitative pipeline).
3. **Casimir-Entropy [8]:** proposes *how* to test it in the laboratory (modulated Casimir effect).

8.7. Observational Hints: Where Standard Cosmology Shows Cracks

Beyond the logical arguments developed in this paper, recent observations indicate empirical pressure points where the standard ΛCDM picture requires ad hoc additions and where the present framework provides a natural language without yet making sharp quantitative predictions. We list them briefly as motivation for further investigation rather than as decisive evidence; in each case the literature remains active and alternative explanations exist within ΛCDM. The reanalysis of the SDP.81 gravitational lens by Stacey et al. [47], following earlier substructure claims [48,49], raises questions about the robustness of dark-matter subhalo detection and is structurally compatible with a smoother effective potential of the kind expected from entropic coarse-graining. The persistent diversity of dwarf-galaxy rotation curves and their correlation with baryonic structure [50] is naturally formulated as a memory-of-baryons effect, with the testable signature that wiggles should correlate with current gas morphology with a characteristic lag rather than being stochastic. The 2–3σ pressure tension in the Bullet Cluster combining ALMA and X-ray data [51] occurs in precisely the far-from-equilibrium regime where the hysteresis kernel of Chapter 7 predicts deviations from instantaneous hydrodynamics. Quantitative predictions for each of these channels require the dynamical framework of the companion paper [7] and are not derived here; what we record is the structural compatibility, not a fit.

8.8. Phase Coherence and the CMB (Summary)

As developed in Sec. 6.13, the "phase coherence problem" of the CMB is reframed in the holographic framework: if CMB peaks are understood as *normal modes of the boundary* rather than oscillations with free phases, coherence becomes a property of the modal structure, like the frequencies of a drum. This is a conceptual reframing; reproducing the observed peak positions and heights quantitatively is left to future work.

This reframing:

- Removes the need for a Bunch-Davies vacuum to explain phase alignment
- Derives the amplitude $\delta T/T \sim 10^{-5}$ from $1/\sqrt{N_{\rm eff}}$ (boundary statistics)
- Interprets low-ℓ anomalies as potential signatures of boundary geometry

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The framework makes a strong consistency requirement: the same parameters must fit CMB, galactic dynamics, and dark energy. This global fit is the natural next step.

8.9. Future Tests and Scientific Risk

The framework exposes itself to empirical risk:

- **LiteBIRD** (∼2028): will reach $\sigma(r) \sim 10^{-3}$. A detection of $r > 10^{-2}$ with confirmed primordial origin would falsify the minimal framework.
- **CMB anomalies**: continued study of low-ℓ deficit and axis alignments.
- **Laboratory tests**: modulated Casimir measurements [8].

8.10. The Deeper Point: Why an Entropic Description Is Strongly Motivated

A skeptic might object: replacing "why does the universe expand?" with "why does entropy increase?" merely shifts the question without answering it. This objection misses an asymmetry already noted in the Positioning section. In the classical picture, spacetime is an isolated primitive: its quantities (coordinates, metric, intervals) have no microstructure, no informational content, no connection to the language of the rest of physics. The entropic-holographic framework removes this isolation: spacetime acquires microstructure (boundary degrees of freedom), entropy (area in Planck units), bounds (Bekenstein–Bousso), and an emergent character (geometry from entanglement, Sec. 4.5). The explanatory gain is not that we have answered an ultimate "why"; it is that we have connected what was disconnected.

The alternatives appear limited: either accept that spacetime is emergent and informational (the path argued in this paper), or keep spacetime as an isolated primitive and accept that unification with quantum physics remains impossible without modifications to General Relativity more costly than the present proposal. we do not claim this is the only possible path. we claim it is the path that survives once the alternatives are taken seriously, and that it makes predictions that can prove me wrong.

8.11. Concluding Synthesis

We began with a freshman's question: if the universe contains so much mass in a region comparable to its gravitational radius, why isn't it a black hole?

The answer, it turns out, is that the question was right—but the premise was incomplete. The universe is not a *container* of mass-energy that somehow avoids collapse. It is a *projection* of information encoded on a causal boundary. The three-dimensional space we inhabit is not where physics fundamentally happens; it is where physics *appears* after coarse-graining from holographic degrees of freedom.

Within the minimal assumptions adopted here, this shift in perspective is difficult to avoid; it follows from the combination of:

- the algebraic identity $R_p \lesssim R_g$ that holds in every cosmic epoch,
- the causal no-go that excludes the black hole interpretation,
- the covariant entropy bounds that exclude volumetric information storage.

Once we accept that space is emergent, time follows: it cannot be a fundamental axis if the arena it parametrizes is itself a reconstruction. Time becomes the measure of entropic accumulation—the counting of how much history has been written on the boundary.

And if time is entropic, the past acquires physical weight. It does not simply vanish; it leaves traces in the form of non-Markovian memory effects that shape present dynamics. This is entropic hysteresis: the universe remembers.

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The framework makes falsifiable predictions. If LiteBIRD detects primordial tensor modes at $r > 10^{-2}$, the minimal version is falsified. If large local non-Gaussianity is found ($|f_{\rm NL}| \gg 5$), the CLT origin of perturbations is excluded. These are the predictions on which the proposal stands or falls.

The initial observation—that the observable mass-energy and its gravitational scale stay close together across every cosmic epoch—is not a curious accident. It is a structural feature of the Friedmann equations themselves. Recognizing it does not require new physics. It requires taking the existing equations seriously and following the consequences where they lead.

Final Methodological Note

The framework makes specific predictions that future experiments will test:

- $r < 10^{-3}$: LiteBIRD (∼2028) will reach sensitivity $\sigma(r) \sim 10^{-3}$
- $|f_{\rm NL}^{\rm local}| \lesssim 5$: consistent with current limits, testable with future surveys
- Low-ℓ anomalies: expected from finite boundary, to be quantified

If these predictions are contradicted by observation, the minimal framework is falsified.

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Appendix A. Explicit Derivation of the Global Gravitational Constraint

Appendix A.1. Minimal Assumptions and Context

The entire derivation is based exclusively on:

- Classical General Relativity;
- Homogeneous and isotropic FRW metric;
- Spatially flat Universe ($k = 0$), in agreement with observations;
- Standard definitions of cosmological horizons.

No new dynamical hypothesis or physical entity is introduced.

Appendix A.2. Friedmann Equations

The Friedmann equation for a flat universe is:

$$H^2(t) = \frac{8\pi G}{3}\rho(t)\,, \tag{A1}$$

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where $\rho(t)$ is the total energy density (radiation, matter, dark energy).

Appendix A.3. Particle Horizon as Observable Scale

The particle horizon is the maximum causal distance:

$$R_p(t) = a(t) \int_0^t \frac{c\,dt'}{a(t')}. \tag{A2}$$

Appendix A.4. Mass-Energy Contained in the Observable Universe

$$M(t) = \frac{4\pi}{3}\rho(t) R_p^3(t). \tag{A3}$$

Appendix A.5. Associated Gravitational Radius

$$R_g(t) = \frac{2GM(t)}{c^2}. \tag{A4}$$

Appendix A.6. Insertion of Friedmann

Substituting $\rho = 3H^2/(8\pi G)$:

$$R_g(t) = \frac{H^2(t)}{c^2} R_p^3(t) = \frac{R_p^3(t)}{R_H^2(t)}. \tag{A5}$$

Appendix A.7. Ratio Between Scales

$$\frac{R_p(t)}{R_g(t)} = \left(\frac{R_H(t)}{R_p(t)}\right)^2. \tag{A6}$$

Since $R_p \geq R_H$ for expanding universes, we have $R_p/R_g \leq 1$.

Appendix A.8. Validity in All Cosmic Epochs

The identity holds independently of the dominant component (radiation, matter, Λ).

Appendix A.9. Effect of Spatial Curvature $k \neq 0$

For non-flat universes, the constraint is modified but not eliminated. The correction is of order $|\Omega_k|$, observationally constrained to $|\Omega_k| \lesssim 0.005$ at 95% CL from Planck 2018 in combination with BAO data [21].

Appendix B. Historical Section: Gravity, Entropy and Information

Appendix B.1. From Classical Gravity to the First Conceptual Shock

Before 1970, gravity was pure geometry. Bekenstein changed everything.

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Appendix B.2. Bekenstein: Entropy Enters Gravity

Bekenstein [19] proposed that black holes have entropy proportional to their horizon area:

$$S_{\rm BH} = \frac{k_B c^3}{4G\hbar} A = \frac{A}{4\ell_P^2}. \tag{A7}$$

Appendix B.3. Hawking: The Final Blow

Hawking [20] showed that black holes emit thermal radiation with temperature:

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}. \tag{A8}$$

Appendix B.4. 't Hooft and Susskind: the Holographic Principle Is Born

If maximum entropy scales with area, fundamental degrees of freedom must be "on the boundary," not in the volume [2,3].

Appendix B.5. Covariant Bound and Cosmology

Bousso [4] formulated the covariant entropy bound, applicable to any causal surface. Padmanabhan [1,10] and Cai and Kim [11] developed the thermodynamic equivalence between the Friedmann equations and horizon thermodynamics, providing the technical basis on which Theorem 1 rests. Banks and Fischler [14] proposed holographic cosmology as a programme; the present argument can be read as a bottom-up version of that programme, derived from minimal assumptions rather than postulated.

Appendix B.6. The Missing Step

This paper completes the logical chain by applying these principles to the entire observable Universe, with falsifiable consequences.

Appendix C — Graphical Supplement

Figure A1. Minkowski causality reminder. Dimensional comparability of scales is not sufficient to identify two geometries; what determines geometric identity is the structure of the light cones and the resulting causal structure. The figure recalls why the question raised in Chapter 1 is causal before being numerical; the cosmological metric is not reducible to a Minkowski patch, but the Minkowski analogue captures the structural distinction that motivates Theorem 2.

Appendix C. Appendix D — Explicit Integration with the Corpus

This article is part of a corpus of works developing the same framework:

D.1 Entropic time (Ch. 5 here → companion)

The operational definition τ_S is introduced here; the full derivation and quantitative pipeline are in [7].

D.2 $N_{\rm eff}$ prescription (Ch. 6 here → complete pipeline)

The sanity check on A_s is performed here; the complete statistical derivation is in [7].

D.3 Memory kernel K_R (Ch. 7 here → Schwinger–Keldysh derivation)

The outline is given here; the full derivation from open quantum system theory is in [7].

D.4 Laboratory bridge (Casimir)

The connection between cosmological coarse-graining and laboratory-scale effects is developed in [8].

D.5 Recommended reading strategy

1. This paper (Foundation): *why* holography is necessary.
2. Hysteresis paper: *how* the mechanism works.
3. Casimir paper: *how* to test it in the laboratory.

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