5. Discussion: Why does information shape spacetime?

5.1 Gravity as an informational response

Gravity appears, at first glance, as one of nature's fundamental interactions. Yet within this framework, a different picture emerges—radical in implication, but natural in origin: gravity is not a fundamental force, but an emergent, geometric response to how quantum information is distributed, compressed, and rendered irreversible across spacetime.

What is radical is the demotion of gravity from a primary interaction to a derived phenomenon. What is natural is that spacetime geometry should respond to information, once information is recognized as a physical quantity subject to dynamical laws.

This perspective follows a well-established intellectual lineage. Jacobson (1995) demonstrated that Einstein's equations can be obtained from thermodynamic relations, while Verlinde (2011) interpreted gravity as an entropic force associated with holographic information. Our framework does not reject these insights—it completes them. Rather than treating entropy as a static property of horizons or screens, we introduce quantum relative entropy $D(\rho \| \sigma)$ as a time-evolving, dynamical measure of informational divergence between the actual quantum state of spacetime (ρ) and a reference geometry (σ) determined solely by classical matter content.

In this formulation, Einstein's equations,

$$G_{\mu\nu} + \Lambda_{eff} g_{\mu\nu} = 8\pi G T_{\mu\nu},$$

are not fundamental laws imposed upon spacetime. They arise instead as the low-energy, semiclassical limit of a deeper informational dynamics—valid precisely in regimes where the informational divergence evolves slowly and locally. The effective cosmological constant Λ_{eff} is therefore not a parameter to be tuned, but a geometric imprint of the global organization of quantum information across cosmic history.

Crucially, this framework is not a reinterpretation layered atop existing physics. It is predictive by construction. The time dependence of $D(\rho\|\sigma)$, driven by coarse-graining during structure formation and constrained by future boundary conditions, leads inevitably to late-time cosmic acceleration and to a characteristic enhancement of the Integrated Sachs–Wolfe effect. These phenomena are not postdictions retrofitted to observation; they are the unavoidable consequences of taking information geometry seriously as the foundation of spacetime dynamics.

5.2 Why late-time acceleration?

The question "Why now?" has haunted cosmology since the discovery of cosmic acceleration. Within ΛCDM, the answer remains deeply unsatisfying: the cosmological constant simply exists, and its extreme smallness relative to the Planck scale—yet dominance precisely in the present epoch—appears as an unexplained coincidence.

Our framework replaces coincidence with inevitability.

The early universe is informationally simple. At high redshift ($z \gg 1$), quantum degrees of freedom are distributed nearly homogeneously, and correlations have not yet been localized by structure formation. In this regime, coarse-grained Rényi entropies remain small, the effective geometry $\rho_{\mu\nu}$ is indistinguishable from the reference metric $\sigma_{\mu\nu}$, and the informational divergence $D(\rho\|\sigma)$ is negligible. Gravity follows the familiar radiation- and matter-dominated expansion, accurately described by classical dynamics.

Structure formation compresses information. As the universe cools and nonlinear structures emerge, quantum information becomes increasingly localized—concentrated into galaxies, clusters, and the cosmic web. This localization is inherently irreversible: coarse-graining over unresolved degrees of freedom steadily increases informational entropy. The geometry ρ begins to depart from σ, not abruptly, but cumulatively. The informational landscape is carved slowly, as complexity accumulates.

The influence of the future boundary becomes dynamically relevant. At low redshift ($z \lesssim 1$), a qualitatively new regime appears. The weak boundary condition imposed at future null infinity $\mathscr{I}^+$—representing the asymptotic approach toward a quasi-equilibrium informational state—begins to constrain the present evolution of spacetime geometry. This does not introduce retrocausality. Rather, it reflects a global consistency condition: the present geometry must evolve along trajectories compatible with its allowed asymptotic informational configuration. As this constraint tightens, the growth of Rényi entropy accelerates, the divergence $D(\rho\|\sigma)$ increases rapidly, and this informational acceleration manifests geometrically as cosmic acceleration.

The coincidence dissolves. Acceleration is observed at $z \approx 0.7$ not because of fine-tuning, but because this epoch marks the intersection of three necessary conditions: sufficient structural complexity to compress information, sufficient cosmic age for future boundary constraints to become effective, and a maximal informational gradient dD/dz. Only when all three are simultaneously satisfied does accelerated expansion emerge.

Late-time acceleration is therefore neither eternal nor accidental. It is a transient, non-equilibrium phase in the informational geometry of spacetime—one that inevitably arises during cosmic evolution and saturates as the universe approaches its asymptotic state.

Cosmic acceleration is not a parameter to be chosen. It is a phase transition through which spacetime learns how it must end.

5.3 The ISW effect as an information-theoretic transient

A universe that accelerates only briefly cannot do so silently. If late-time acceleration is a transient phase in the informational evolution of spacetime, it must leave an observable scar.

The most direct manifestation of this scar is the Integrated Sachs–Wolfe (ISW) effect.

ISW as a probe of evolving informational geometry. CMB photons traversing large-scale structures gain or lose energy when gravitational potentials evolve in time. In the standard ΛCDM scenario, this evolution is mild: the cosmological constant induces a slow decay of potential wells at late times, producing a weak ISW signal correlated with large-scale structure. Observationally, this signal remains marginal, detected at approximately 2–3 σ significance in current data.

In our framework, the ISW signal is enhanced—and unavoidably so. The late-time growth of the informational divergence $D(\rho \| \sigma)$ implies a rapid evolution of gravitational potentials beyond that expected in ΛCDM. Because the effective geometry ρ responds dynamically to the increasing informational gradient, the time derivative of the gravitational potential is amplified. The resulting ISW enhancement is not a tunable feature, nor a phenomenological adjustment—it is a direct geometric consequence of spacetime undergoing a non-equilibrium informational transition.

This framework leads to concrete predictions:

- an enhancement of the ISW amplitude by approximately 25–35% at large angular scales ($\ell \lesssim 30$),
- a maximal contribution at low redshift ($z \lesssim 0.5$), coincident with the peak growth rate of $D(\rho \| \sigma)$,
- and a smooth convergence to ΛCDM expectations at higher redshift ($z \gtrsim 1.5$), where informational divergence remains negligible.

These features arise inevitably from the transient nature of late-time acceleration. The ISW signal exists because the present epoch occupies a narrow informational window: late enough for global boundary constraints to shape spacetime dynamics, yet early enough that informational divergence has not saturated.

The ISW effect is therefore not incidental. It is the observational imprint of spacetime learning how it must end under global informational constraints.

Forthcoming high-precision measurements of large-scale structure and CMB temperature anisotropies will decisively test this prediction. An enhanced ISW signal at the predicted scales would elevate the detection significance to the level of a definitive measurement, while its absence would rule out this framework. In this sense, the ISW effect is not merely a forecast—it is the experiment that the universe has already prepared.

A universe that accelerates briefly must leave a scar in the CMB. We propose that scar is the ISW effect, and that its depth encodes the rate at which spacetime is learning its own ending.

5.4 Relation to holography and quantum gravity

This framework does not present itself as a UV-complete theory of quantum gravity. It is an effective description, formulated deliberately at the semi-classical level where spacetime geometry remains meaningful and observable. This limitation is not a weakness—it is a boundary condition. Within that boundary, however, the framework exhibits deep structural affinities with holographic approaches to gravity, suggesting that it may be pointing toward the correct microscopic language.

Boundaries as informational constraints. In holographic theories such as AdS/CFT, bulk geometry is not autonomous: it is constrained, and in a precise sense determined, by degrees of freedom living on a boundary. Entropy and entanglement are not secondary quantities but organizing principles. Our framework adopts this logic in a cosmological setting. The effective metric $\rho_{\mu\nu}$ responds not only to local stress-energy but also to global informational constraints imposed at future null infinity $\mathcal{I}^+$.

Crucially, this boundary condition is not an external input chosen for convenience. It reflects a consistency requirement: spacetime geometry must evolve in a way that is compatible with the universe's asymptotic informational structure. In this sense, the future boundary plays a role analogous to holographic screens—not as a locus of dynamics, but as a constraint that shapes which bulk geometries are admissible.

Rényi entropy and holographic robustness. The choice of Rényi-2 entropy as the fundamental coarse-graining measure is not arbitrary. In holographic contexts, Rényi entropies occupy a privileged position: they admit clean geometric representations via the replica trick and remain well-defined across a wide range of microscopic theories. By employing Rényi entropy in a cosmological setting, we exploit this robustness. The entropy $S_2(x)$ quantifies how quantum information is distributed and compressed throughout cosmic history, providing a bridge between microscopic entanglement structure and macroscopic spacetime geometry.

In this framework, late-time acceleration emerges not from vacuum energy, but from the growing mismatch between the informational organization of spacetime and its classical geometric description.

Information geometry as the common language. At the core of the construction lies the quantum relative entropy $D(\rho\|\sigma)$. In quantum information theory, this quantity is canonical: it measures distinguishability, obeys monotonicity under coarse-graining, and defines a natural geometry on the space of quantum states. By coupling this geometric object directly to spacetime curvature, we propose that gravity is most naturally described not in terms of forces or fields, but as a response within information geometry.

This perspective unifies and extends earlier insights. Jacobson's thermodynamic derivation of Einstein's equations identifies entropy as foundational. Verlinde's entropic gravity emphasizes information flow and displacement. Our framework completes this trajectory by making informational divergence explicitly dynamical and time-dependent, allowing the geometry itself to evolve in response to changing informational structure.

Scope and open directions. A complete theory of quantum gravity would derive the effective metric $\rho_\mu\nu$from microscopic degrees of freedom, specify the origin of the future boundary condition, and explain the emergence of information geometry from first principles. We do not claim to have accomplished this. What we provide instead is a coherent, predictive framework that isolates the relevant macroscopic variables and connects them directly to observation.

The significance of this approach does not lie in finality. It lies in translation.

If gravity is emergent, then the question is not which quantum gravity theory is correct, but which language nature uses when spacetime responds to information. This framework suggests that language is information geometry—and that the universe is already answering us, through its late-time acceleration and the scars it leaves in the cosmic microwave background.

5.5 What this framework does not claim

Clarity requires honesty about scope. A theory gains strength not only from what it explains, but from what it explicitly does not attempt to explain. We state these limits plainly.

This is not a UV-complete quantum gravity theory. We do not derive the effective metric $\rho_{\mu\nu}$ from first principles in string theory, loop quantum gravity, or any other microscopic framework. We do not specify the fundamental degrees of freedom, nor do we claim to resolve the measurement problem, the black hole information paradox, or the nature of quantum spacetime at the Planck scale. These questions lie beyond the scope of this work.

This is not a modification of quantum mechanics. The framework operates entirely within standard quantum theory and semi-classical gravity. The use of reduced density matrices, Rényi entropy, and quantum relative entropy involves no new axioms, no hidden variables, and no departure from unitarity. The future boundary condition at $\mathscr{I}^+$ is imposed as a global consistency constraint, not as a retrocausal mechanism or a collapse postulate.

This is not a solution to the cosmological constant problem in its traditional form. We do not explain why the vacuum energy density is 120 orders of magnitude smaller than naive quantum field theory estimates. What we provide is a reframing: rather than treating Λ as a fundamental parameter requiring fine-tuning, we show how an effective $\Lambda_{eff}(z)$ can emerge dynamically from the informational structure of spacetime. The deep question—why the Planck-scale vacuum energy does not gravitate—remains open.

This framework does not uniquely determine all cosmological observables. Our predictions are specific to phenomena directly coupled to the informational divergence $D(\rho\|\sigma)$: late-time acceleration, the ISW effect, and potentially the alleviation of H_0 and σ_8 tensions. For observables dominated by early-universe physics—such as primordial power spectra, baryogenesis, or inflation—this framework defers to standard treatments. It is a late-time, large-scale effective description, not a theory of everything.

What this framework does claim.

Within its stated domain—semi-classical cosmology at late times and large scales—this framework makes three definite, falsifiable assertions:

1. **Cosmic acceleration is not due to a cosmological constant, but to the geometric manifestation of quantum relative entropy between two semi-classical metrics.**
2. **The Integrated Sachs-Wolfe effect is enhanced by 25–35% at large angular scales relative to ΛCDM** (based on preliminary semi-analytic estimates), **as a direct consequence of the accelerating informational gradient.**
3. **This enhancement will be detected or ruled out within 5 years by cross-correlations between large-scale structure surveys and CMB observations.**

If observation contradicts these predictions, the framework is falsified. If observation confirms them, the framework survives—and the question becomes whether nature truly speaks the language of information geometry, or whether this success is a coincidence that a deeper theory will later explain.

The value of incomplete theories.

Science does not progress only through complete theories. Effective descriptions that isolate the right variables, make testable predictions, and connect disparate phenomena often prove more fertile than premature attempts at finality. This framework aspires to that role.

We do not claim to have found the final theory of gravity. We claim to have found a language in which late-time cosmology becomes simpler, more predictive, and more deeply connected to the principles of quantum information.

Whether that language is fundamental, or merely effective, is a question we leave to observation. And to those who will build on this work.