The Cosmological Constant as Horizon Thermodynamics: An Unruh Perspective on Dark Energy—Why Now?

A Speculative Note

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Abstract

We argue that the cosmological constant Λ is the thermodynamic signature of the universe's cosmological event horizon. Starting from the Unruh effect and the holographic bound, we recover the observed dark energy density as thermal energy dissipated across the horizon. The fixed-point condition $\rho_{\rm thermal} = \rho_\Lambda$ holds exactly in de Sitter spacetime and uniquely for the maximum-entropy relation $E = TS$, yielding a parameter-free prediction $c = 1$ for the holographic dark energy model and a present-day equation of state $w \approx -0.89$ with $w \geq -1$ at all times. The generalized second law reinforces this prohibition, suppressing phantom crossing by $e^{-10^{122}}$. DESI DR2 favors evolving dark energy at 2.8–4.2σ, consistent with this picture; whether phantom crossing is real will be tested by forthcoming data. The equilibration time to de Sitter, $t_{\rm eq} \sim 10^{10}$ years, is comparable to the present age of the universe, resolving the coincidence problem thermodynamically. If Λ is determined by horizon thermodynamics rather than environmental selection, the anthropic principle becomes unnecessary.

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1 Context

The idea that dark energy arises from the thermodynamics of cosmological horizons has a substantial history. Jacobson [1] derived the Einstein equations from $\delta Q = T\,dS$ on local Rindler horizons. Cohen, Kaplan, and Nelson [2] showed that the holographic bound with a cosmological IR cutoff yields the correct vacuum energy density. Li [3] built a concrete holographic dark energy model using the future event horizon, founding an active subfield [4]. Padmanabhan [5–7] developed an extensive program connecting cosmological dynamics to horizon thermodynamics. Komatsu [8] showed that the horizon energy via holographic equipartition is consistent with the observed Λ.

This note does not claim priority over these results. Its aim is to organize them into a single narrative beginning with the Unruh effect, with Noether's theorem providing the interpretive bridge: Λ is the rate of irreversible thermodynamic dissipation across the cosmological horizon.

2 The Argument

The logical path at the foundation of this note can be sketched in three steps: (1) accelerating expansion produces a horizon with a well-defined temperature; (2) the horizon temperature implies thermal radiation and entropy; (3) holographic scaling fixes the energy density of that radiation, which we identify with dark energy.

Step 1. A uniformly accelerating observer perceives a thermal bath at temperature $T = \hbar a/(2\pi c_\ell k_B)$[1] [9, 10]. The thermal spectrum arises because the observer's Rindler horizon traces over modes behind the causal boundary. Our universe's accelerating expansion produces an analogous cosmological event horizon at $r_H \approx 1.5 \times 10^{26}\,\mathrm{m}$. Gibbons and Hawking [11] showed it has temperature $T_{\mathrm{GH}} = \hbar H/(2\pi k_B)$, where H is the Hubble parameter governing the expansion [12].

Step 2. The horizon carries Bekenstein–Hawking entropy $S = k_B A/(4\ell_P^2) \sim 10^{122}\, k_B$. With temperature $T \sim 10^{-30}\,\mathrm{K}$, the thermal energy density follows directly from horizon thermodynamics: $\rho \sim TS/(Vc_\ell^2) \approx 10^{-26}\ \mathrm{kg/m^3}$, matching the observed dark energy density.

Step 3. The Bekenstein–Hawking entropy used in Step 2 already embodies area scaling; the holographic principle [13, 14] makes this explicit by bounding degrees of freedom by the horizon *area*, not the volume. **The central assumption of this note enters here:** the vacuum energy density scales holographically with the horizon, $\rho \propto 1/R_E^2$, as proposed by Cohen, Kaplan, and Nelson [2] and Li [3]. This is motivated by quantum gravity but not derived from first principles. With the cosmological horizon as IR cutoff, holographic scaling gives $\rho \sim c^2/(Gr_H^2) \approx 6 \times 10^{-26}\ \mathrm{kg/m^3}$, where c is a dimensionless holographic parameter (not to be confused with the speed of light c_ℓ)—in agreement with the thermodynamic estimate of Step 2. Section 4 shows that de Sitter is a thermodynamic attractor at which the holographic bound is saturated ($c = 1$); saturation need not be imposed as a separate postulate. What remains unexplained is why the vacuum energy follows the holographic scaling at all; if it does, the results below follow as consequences.

The overall premise, then, is that the thermal energy dissipated across the cosmological horizon is counterbalanced by the dark energy term: what the observable universe loses as irreversible radiation, it gains as Λ. In an accelerating spacetime, time translation symmetry is broken and Noether's theorem permits precisely this form of energy non-conservation [15, 16]. The horizon thermodynamics specifies its form—steady, featureless, maximal-entropy dissipation—which is the cosmological constant.

3 The Fixed-Point Equation

We test this claim by writing down the self-consistency condition explicitly. In natural units ($c_\ell = \hbar = k_B = 1$), a pure de Sitter spacetime with cosmological constant Λ has:

$$r_H = \sqrt{3/\Lambda}\,, \quad T = \frac{1}{2\pi}\sqrt{\Lambda/3}\,, \quad S = \frac{3\pi}{G\Lambda}\,, \quad V = \frac{4\sqrt{3}\,\pi}{\Lambda^{3/2}}\,. \tag{1}$$

[1] Throughout this note, c_ℓ denotes the speed of light, to avoid confusion with the holographic parameter c introduced in Section 4.

A direct calculation gives:

$$\rho_{\text{thermal}} = \frac{TS}{V} = \frac{\Lambda}{8\pi G} = \rho_\Lambda \,. \tag{2}$$

The ratio is exactly unity. The de Sitter universe sits precisely at the thermodynamic fixed point.

This identity holds for *any* Λ, so in its present form it does not select a particular value. The thermodynamic condition is universal—it applies in every causal patch—but the value of Λ (and hence the dark energy density) may differ from patch to patch; the framework constrains the *relationship* between vacuum energy and horizon properties, not the specific magnitude. However, it is sensitive to the thermodynamic relation assumed: writing $E = \alpha TS$, the ratio becomes $\rho_{\text{thermal}}/\rho_\Lambda = \alpha$. Only $\alpha = 1$—the maximum-entropy relation—yields exact self-consistency. Padmanabhan's equipartition ($\alpha = 2$) and the canonical $E = \frac{1}{2}TS$ ($\alpha = \frac{1}{2}$) do not. This singles out the de Sitter state as the unique thermodynamic equilibrium.

The real constraint emerges for realistic cosmologies. Our universe contains matter and radiation; the horizon evolves. The dynamical condition

$$\rho_{\text{dark}}(t) = \frac{T(t)\, S(t)}{V(t)} \tag{3}$$

is no longer an identity but a genuine constraint on $\rho_{\text{dark}}(t)$ and the equation of state $w(t)$. The pure de Sitter identity (2) appears as the late-time attractor. Developing (3) into a full dynamical framework is beyond this note but may represent the natural next step.

4 Horizon Choice and the Generalized Second Law

The fixed-point identity (2) was derived for pure de Sitter, where the Hubble horizon and the cosmological event horizon coincide at $r_H = 1/H$. In a realistic universe containing matter, they do not. The Hubble horizon gives $TS/V = 3H^2/(8\pi G) = \rho_{\text{total}}$, which would require $\rho_{\text{matter}} = 0$—inconsistent with observation. This is the well-known reason that Li [3] adopted the future event horizon R_E as the infrared cutoff.

The thermodynamic framework selects the same choice on physical grounds: the future event horizon is the true causal boundary—the surface beyond which signals emitted today will never reach us. It is this boundary across which information is irreversibly lost, and it is therefore the correct surface on which to define the horizon temperature and entropy. With R_E as the thermodynamic surface:

$$\rho_{\text{dark}} = \frac{T\, S}{V} = \frac{3}{8\pi G\, R_E^2} \,. \tag{4}$$

Li's holographic dark energy model [3, 4] writes this as $\rho_{\text{dark}} = 3c^2/(8\pi G\, R_E^2)$, where c is a free parameter fit to observation; current data give $c \approx 0.8$–1.2. Our $\alpha = 1$ uniqueness result from Section 3 *predicts* $c = 1$ with no free parameters. This is a testable, parameter-free prediction of the thermodynamic framework.

The generalized second law (GSL) provides an independent consistency check. The event horizon entropy is $S_E = \pi R_E^2/G$, and the event horizon satisfies $\dot{R}_E = HR_E - 1$ [3]. Therefore:

$$\frac{dS_E}{dt} = \frac{2\pi R_E}{G}\left(HR_E - 1\right) . \tag{5}$$

In a universe with matter and dark energy, $R_E > 1/H$ at all times during the expanding phase. The GSL is therefore satisfied: $dS_E/dt > 0$. As the universe approaches de Sitter, $R_E \to 1/H$ and $dS_E/dt \to 0$: the entropy growth halts and the horizon reaches maximum entropy. De Sitter is not merely a fixed point of the thermodynamic condition—it is the *maximum-entropy equilibrium* toward which the second law drives the universe.

A pattern emerges: the thermodynamic framework consistently selects *critical values*—boundary points between physically distinct regimes. The parameter $\alpha = 1$ is the unique value at which the fixed-point equation holds. The prediction $c = 1$ sits exactly at the boundary between phantom energy ($c < 1$, $w < -1$, Big Rip) and weak quintessence ($c > 1$, $w \gg -1$). The condition $\Lambda \geq 0$ is the boundary between de Sitter (horizon exists) and anti-de Sitter (no horizon). The de Sitter state itself sits at $dS_E/dt = 0$, the boundary between entropy growth and decrease. This is characteristic of thermodynamic equilibria in general: they are extrema, and extrema are boundaries. The observed universe, in this reading, sits at a cosmological critical point.

These critical values are not merely special—they are *stable*. A perturbation analysis reveals three complementary stability mechanisms. First, within Li's holographic dark energy model, $\Omega_{\rm de} = 1$ is a stable attractor: near $\Omega_{\rm de} = 1-\epsilon$, the evolution equation gives $\Omega'_{\rm de} \approx (1+2/c)\,\epsilon > 0$, so the dark energy fraction is driven exponentially toward unity for any $c > 0$. Second, the GSL enforces $R_E \geq 1/H$: states with $R_E < 1/H$ would have $dS_E/dt < 0$, violating the second law, so the universe can only approach de Sitter from above, monotonically, without overshooting. Third, the equation of state converges as $w + 1 \sim \epsilon/3 \sim e^{-3a}$, where a is the scale factor—exponential approach to $w = -1$ at late times. The pure de Sitter fixed-point condition itself ($\alpha = 1$) is marginally stable, as expected for an identity that holds for any Λ; the non-trivial stability comes from the matter-coupled dynamics. Together, these mechanisms ensure that the de Sitter critical point is a stable equilibrium: the universe is driven toward it by the second law, held there by the attractor dynamics of $\Omega_{\rm de}$, and forbidden from overshooting by the GSL.

The exponential approach has a concrete timescale. Today $\Omega_{\rm de} \approx 0.7$ and $\epsilon \equiv 1 - \Omega_{\rm de} \approx 0.3$. With $c = 1$, the evolution equation gives $\Omega'_{\rm de} \approx 3\epsilon$, so ϵ decreases by a factor of e per e-fold of expansion—equivalently, per Hubble time $H^{-1} \approx 1.4 \times 10^{10}$ years. Reaching $\epsilon < 10^{-2}$ requires $\ln(0.3/0.01) \approx 3.4$ e-folds, or roughly $t_{\rm eq} \sim 3$–$4\ H^{-1} \sim 4$–5×10^{10} years from the present epoch. We define $t_{\rm eq}$ as this *equilibration time*—the timescale on which the universe reaches thermodynamic equilibrium. That the generalized second law drives the universe toward de Sitter as a maximum-entropy state has been proved rigorously by Carroll and Chatwin-Davies [17], who term this process "cosmic equilibration"; the attractor properties of de Sitter are well established in the dynamical-systems literature. What we add here is the concrete timescale and its connection to the coincidence problem. $t_{\rm eq}$ is comparable to the current age of the universe. We observe the cosmos during the brief window between the matter-dominated era, which built all gravitational structure, and the de Sitter equilibrium,

which will erase it. Observers require structure, and structure requires disequilibrium. The much-discussed *coincidence problem*—why $\Omega_{\rm de} \sim \Omega_{\rm matter} \sim \mathcal{O}(1)$ today, when these quantities differ by many orders of magnitude at almost all other epochs—acquires a thermodynamic answer: we necessarily observe during the transition to equilibrium, because only during this transition does the universe contain the structures on which observers depend.

We note that $c = 1$ yields a specific, testable prediction for the dark energy equation of state. In Li's model [3], $w = -1/3 - 2\sqrt{\Omega_{\rm de}}/(3c)$. With $c = 1$ and $\Omega_{\rm de} \approx 0.7$ today, this gives $w_0 \approx -0.89$—still accelerating ($w < -1/3$), but distinguishable from ΛCDM ($w = -1$). The equation of state approaches $w = -1$ only asymptotically as $\Omega_{\rm de} \to 1$. Crucially, $c = 1$ imposes a hard constraint: $w \geq -1$ at all times. The phantom barrier is never crossed. This prohibition is not merely a feature of the model but has thermodynamic weight: a transition to $w < -1$ would require the cosmological horizon entropy ($S \sim 10^{122}\, k_B$) to decrease, which the generalized second law suppresses by a factor of $e^{-\Delta S/k_B} \sim e^{-10^{122}}$. While the GSL is statistical rather than absolute, this suppression is so extreme that an observed phantom crossing cannot be attributed to a thermodynamic fluctuation—it would falsify the framework outright.

Recent results from DESI Data Release 2 [18] report a preference for time-varying dark energy at 2.8–4.2σ significance, depending on the supernova dataset used—broadly consistent with our prediction that $w \neq -1$. The best-fit $w_0 w_a$CDM parametrization hints at a phantom crossing near $z \approx 0.5$, with $w > -1$ today and $w < -1$ in the recent past. However, models without phantom crossing remain compatible with the data at the 2σ level [19], and several analyses suggest the apparent phantom behaviour may be an effective artefact of dark matter–dark energy interactions rather than an intrinsic $w < -1$ phase. The data therefore present two features: evolving dark energy (which our framework predicts) and possible phantom crossing (which our framework strictly forbids). This is a falsifiable prediction—any confirmed observation of $w < -1$ at any redshift would rule out the thermodynamic framework. However, a tension must be acknowledged: Planck CMB data, when fit within the HDE model, prefer $c \approx 0.5$, which would place the equation of state in the phantom regime ($w < -1$) and is inconsistent with $c = 1$ at approximately 2–3σ [20]. This is an instance of the well-known early-universe versus late-universe tension that also underlies the Hubble constant discrepancy: late-universe data (BAO, supernovae) favor $c \gtrsim 1$, while CMB data pull toward $c < 1$. Our prediction $c = 1$ sits at the boundary between these regimes. However, this tension admits a natural interpretation within the thermodynamic framework: the condition $c = 1$ is an *equilibrium* prediction, valid at the de Sitter attractor. At the CMB epoch ($z \approx 1100$), the universe was deep in matter domination, far from thermodynamic equilibrium—$R_E \gg 1/H$ and $dS_E/dt \gg 0$. More fundamentally, in a pure matter or radiation universe the future event horizon does not exist at all ($R_E \to \infty$); it is the presence of dark energy that makes R_E finite. The thermodynamic framework built on R_E therefore *cannot apply* at early times in the same sense—the very object on which it rests is absent. Fitting a constant c to early-universe data necessarily yields a value reflecting a regime in which the holographic parameter has no thermodynamic meaning, not the asymptotic critical point. The framework predicts that the *effective* c evolves toward unity as the universe approaches de Sitter, rather than being a fixed constant at all epochs. If the tension resolves in favor of late-universe measurements, the thermodynamic framework is supported; if future data confirm $c < 1$ even at low redshift, it is ruled out. Forthcoming data from Euclid (first cosmology release expected late 2026), the Vera

C. Rubin Observatory, the Nancy Grace Roman Space Telescope, and DESI Data Release 3 will be decisive: if they confirm phantom crossing at high significance, the thermodynamic framework—and, arguably, the generalized second law applied to cosmological horizons—is ruled out.

5 What This Resolves

The magnitude problem: the 10^{120} discrepancy vanishes because the holographic bound counts degrees of freedom by area, not volume. **The coincidence problem:** if dark energy is tied to the evolving horizon, $\rho_{\rm dark}$ tracks $\rho_{\rm matter}$ dynamically rather than by accident. The equilibration time $t_{\rm eq}$ is comparable to the age of the universe (Section 4), so the present epoch $\Omega_{\rm de} \approx 0.7$ is not a coincidence but a necessary feature: observers exist only during the approach to equilibrium, before structure is erased by the de Sitter attractor. **The fine-tuning problem:** ΛCDM treats the cosmological constant as a free parameter to be fit; Li's holographic model replaces it with another free parameter c. The thermodynamic framework eliminates both: $c = 1$ is derived from $\alpha = 1$, and the energy density follows from the horizon. The framework has zero free parameters. **The nature of Λ:** it acquires a microphysical identity as the thermal energy of the cosmological horizon. **Energy non-conservation:** not a puzzle but the expected consequence of broken time symmetry (Noether), with horizon thermodynamics specifying its form. **Self-consistency:** Λ drives the acceleration that creates the horizon that constrains Λ—a fixed-point condition, not a vicious circle [1, 5].

6 The Multiverse and the Anthropic Principle

Where does the dissipated energy go? It crosses the cosmological horizon into causally inaccessible spacetime. In the context of eternal inflation, this is the inflationary substrate from which other bubble universes may nucleate.

The standard approach to the cosmological constant in the multiverse [21, 22] posits that Λ takes different values in different vacua, with our value selected anthropically. The thermodynamic fixed-point picture suggests an alternative: if Λ is determined by self-consistency between the vacuum energy and the thermal energy of the horizon it generates, then Λ is *calculated* within each causally complete region, not selected from a landscape. The argument:

1. A region with vacuum energy Λ creates a horizon of size $r_H \sim c_\ell/\sqrt{\Lambda/3}$.
2. The horizon has temperature T and entropy S.
3. Self-consistency requires $\rho_\Lambda = TS/V$.
4. This is a fixed-point equation: $\Lambda_{\rm input} = \Lambda_{\rm output}$.

Different bubbles may settle to different fixed points, but each is *determined*, not arbitrary. The thermodynamic condition $\rho_\Lambda = TS/V$ with $c = 1$ is the same in every causal patch; the value of Λ is not—it depends on the local vacuum, just as the string landscape suggests.

The framework provides universal dynamics; the landscape provides the initial conditions. The anthropic principle becomes unnecessary—not wrong, but redundant. The explanatory burden shifts from "why this value out of 10^{500}?" to "does the fixed-point equation have a non-trivial solution?"

This extension is the most speculative part of the note. The order-of-magnitude agreement demonstrated above is encouraging but may reflect dimensional consistency rather than a genuine dynamical constraint.

7 What Remains Open

No first-principles derivation is offered for why the vacuum energy follows holographic scaling with the horizon area. The microscopic degrees of freedom of the cosmological horizon remain unidentified. The dimensional analysis may be tautological. If dark energy is dynamically tied to the evolving horizon, the equation of state w may deviate from -1; forthcoming precision measurements from DESI, Euclid (first cosmology release expected late 2026), the Vera C. Rubin Observatory, and the Nancy Grace Roman Space Telescope (launch expected 2027) will test this directly [18].

Three objections deserve explicit comment. First, the holographic dark energy model uses the future event horizon as its IR cutoff, which appears acausal: today's energy density depends on the future evolution. In the thermodynamic reading, however, the horizon is not an input but the self-consistent attractor selected by entropy maximisation—as Carroll and Chatwin-Davies [17] proved from the generalized second law alone, without using the field equations. Second, the fixed-point condition $E = TS$ is an equilibrium relation, yet the universe is not in equilibrium. The resolution is that $E = TS$ is used only to identify the attractor and fix $c = 1$; the non-equilibrium dynamics of the HDE evolution equation then give all observables. Third, the present-day value $w \approx -0.89$ depends on the measured $\Omega_{\rm de} \approx 0.7$ and may therefore seem circular. The actual prediction is the parameter-free curve $w(\Omega_{\rm de}) = -\frac{1}{3} - \frac{2}{3}\sqrt{\Omega_{\rm de}}$, together with the absolute constraint $w \geq -1$ at all redshifts. Both are testable without fitting.

A distinctive prediction of the thermodynamic framework—not shared by Li's model with constant c—is that the effective holographic parameter $c_{\rm eff}$ should *run* with redshift, increasing toward unity as the universe approaches de Sitter equilibrium. Fitting the HDE model to data in separate redshift bins should reveal $c_{\rm eff} < 1$ at high redshift and $c_{\rm eff} \to 1$ at low redshift. In the early-time limit ($\Omega_{\rm de} \to 0$), the equation of state approaches $w \to -\frac{1}{3}$, the boundary between acceleration and deceleration; the transition to the present value $w \approx -0.89$ occurs mostly between $z \sim 2$ and today, squarely within the range probed by current and forthcoming surveys. This running is already implicitly testable with existing DESI data and would constitute direct evidence for the thermodynamic approach to equilibrium. Additionally, since $w > -1$ implies that dark energy was weaker in the past, the framework predicts enhanced structure growth at intermediate redshifts relative to ΛCDM, testable via the growth rate $f\sigma_8(z)$ measured through redshift-space distortions.

8 Concluding Remarks

Every element of this note exists in the literature; the holographic dark energy program and the horizon thermodynamics program have each explored their implications extensively. What has not been done, to our knowledge, is to connect them. The holographic program [2–4] provides the *form* of the dark energy density, $\rho \propto 1/R_E^2$, but leaves the proportionality constant c as a free parameter. The thermodynamic program [1, 5, 6] establishes that horizons carry temperature and entropy, but does not predict the value of Λ. The contribution of this note, if any, is the bridge: the thermodynamic condition $E = TS$ at the horizon *fixes* $c = 1$; the generalized second law *selects* the event horizon; the stability analysis *derives* saturation of the holographic bound; and the second law *drives* the universe toward de Sitter as the maximum-entropy equilibrium. Neither program alone yields a falsifiable prediction. Together, they predict $c = 1$, $w_0 \approx -0.89$, and $w \geq -1$ at all redshifts.

A natural question is whether the framework extends to anti-de Sitter spacetime ($\Lambda < 0$). It does not: AdS has no cosmological event horizon, so the entire chain—horizon $\rightarrow$ thermal energy $\rightarrow$ dissipation $\rightarrow$ Λ—has no analogue. If the self-consistency condition *requires* a horizon, then only $\Lambda \geq 0$ is thermodynamically admissible. This is consistent with the known instability of AdS vacua. More broadly, de Sitter and anti-de Sitter are not merely different signs of Λ but fundamentally different thermodynamic regimes, and only de Sitter supports the horizon-based self-consistency mechanism.

The framework also connects the cosmological constant problem to the information paradox. If Λ is the rate of irreversible information loss across the horizon, the two problems are the same. The Gibbons-Hawking radiation is thermal, carrying no information, in exact parallel with Hawking radiation. If unitarity is fundamental, information cannot be permanently lost, implying that de Sitter is metastable: the universe relaxes *toward* it but unitarity eventually forces departure. The timescale for this departure is not the equilibration time $t_{\rm eq}$ of Section 4—the universe reaches de Sitter in $\sim 10^{10}$ years—but something vastly longer, governed by the de Sitter entropy $S \sim 10^{122}$. The mechanism and timescale remain open questions: unlike a black hole, the cosmological horizon does not evaporate in the standard sense, and whether a Page curve exists for de Sitter is actively debated. In this reading, Λ is not eternal but very slowly decaying—and de Sitter space is not the final state of the universe.

If pressed for a one-sentence summary: *dark energy is the cost of ignorance*—the universe is losing access to its own degrees of freedom, and the energy associated with that loss is what accelerates the expansion.[2]

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