DESI Confrontation and Zero-Parameter Cosmological Scorecard

Abstract

The entanglement entropy framework derives the cosmological constant from the Standard Model field content with zero free parameters, predicting $\Omega_\Lambda = |\delta_{\rm tot}|/(6\,\alpha_{\rm tot}) = 0.6877$ and the equation of state $w = -1$ exactly. We systematically confront these predictions with all available cosmological data, including the DESI DR1/DR2 baryon acoustic oscillation (BAO) measurements, Planck 2018 CMB, multiple supernova compilations, and local distance-ladder determinations of H_0. The framework faces a serious challenge from DESI, whose combined fits prefer $w_0 = -0.75 \pm 0.06$, creating 4.5σ tension with the predicted $w_0 = -1$. However, we demonstrate that this tension is entirely supernova-driven: DESI's own BAO data, analyzed in isolation, *prefers* $w = -1$ over the DESI best-fit $w_0 w_a$CDM model, with $\chi^2/\text{pt} = 1.12$ versus 2.29. A comprehensive zero-parameter scorecard covering 16 independent observables yields $\chi^2/\text{pt} = 1.4$ (excluding two known universal tensions), demonstrating that a single number R derived from particle physics simultaneously matches the expansion rate, cosmic age, BAO distances at six redshifts, and structure growth over 13 billion years. We establish a no-go theorem proving that no modification within the framework can produce $w \neq -1$, making the prediction maximally rigid and maximally falsifiable. A decision tree for DESI DR3 (expected 2027) is presented: if $w \neq -1$ is confirmed at $> 5\sigma$ with consistent supernova samples, the framework is falsified with no escape route.

1 Introduction

The cosmological constant problem—the factor of 10^{122} discrepancy between naive quantum field theory estimates of vacuum energy and the observed dark energy density—remains the most severe fine-tuning problem in fundamental physics. The entanglement entropy framework, developed across a series of companion papers (Moon Walk Project, Papers 1–8), offers a resolution: the cosmological constant Λ is not the total vacuum energy but the entanglement entropy across the cosmological horizon, regulated by the self-consistency condition that relates the horizon area to the entropy it contains.

The framework makes a sharp, zero-parameter prediction for the dark energy density fraction:

$$\Omega_\Lambda = R \equiv \frac{|\delta_{\rm tot}|}{6\,\alpha_{\rm tot}}\,, \tag{1}$$

where $\delta_{\rm tot}$ is the total trace anomaly coefficient summed over all Standard Model (SM) fields plus the graviton, and $\alpha_{\rm tot}$ is the corresponding entanglement entropy area-law coefficient. Both quantities are determined entirely by the field content of the theory—they are UV quantities, insensitive to masses, couplings, or the cosmological expansion history. From this single number, all of LCDM cosmology follows: H_0, the cosmic age, BAO distances, structure growth, and the equation of state $w = -1$.

This paper addresses the most serious challenge the framework has faced: the Dark Energy Spectroscopic Instrument (DESI) data releases, which hint at dynamical dark energy with $w_0 > -1$ at $\sim$ 4–5σ significance. If confirmed, this would *falsify* the framework—there is no tuning parameter, no modification, and no escape route that could accommodate $w \neq -1$. We must therefore confront this challenge with complete honesty.

The structure of the paper is as follows. Section 2 reviews the prediction chain from entanglement entropy to Ω_Λ. Section 3 establishes the rigidity of the $w = -1$ prediction through a no-go theorem covering six classes of modifications. Section 4 presents the full DESI confrontation, including the key finding that DESI's own BAO data prefers the framework over the DESI best-fit $w_0 w_a$CDM. Section 5 addresses the Hubble tension. Section 6 presents the comprehensive zero-parameter scorecard across 16 observables. Section 7 discusses the neutrino mass nature prediction. Section 8 provides the falsification roadmap and decision tree for upcoming experiments. Section 9 concludes.

2 The Prediction: Ω_Λ from Entanglement Entropy

We provide a brief, self-contained summary of the prediction chain; full derivations appear in Papers 1–4 of this series (Moon Walk Project).

2.1 The self-consistency condition

The Jacobson thermodynamic derivation of Einstein's equations requires that the entanglement entropy across a local Rindler horizon satisfies the Clausius relation $\delta Q = T\,dS$ with the Unruh temperature $T = \hbar a/(2\pi c k_B)$. Applied to the cosmological (de Sitter) horizon of area $A_H = 4\pi L_H^2$ with $L_H^2 = 3/\Lambda$, the entanglement entropy of quantum fields takes the form

$$S_{\rm EE} = \alpha_{\rm tot}\,\frac{A_H}{4\ell_{\rm P}^2} + \delta_{\rm tot}\,\ln\!\left(\frac{A_H}{\ell_{\rm P}^2}\right) + \cdots\,, \tag{2}$$

where the area coefficient $\alpha_{\rm tot}$ and the logarithmic coefficient $\delta_{\rm tot}$ are determined by the field content of the theory. The self-consistency condition—that the horizon area implied by Λ matches the entropy that generates Λ via the Clausius relation—yields

$$\Lambda = \frac{|\delta_{\rm tot}|}{2\,\alpha_{\rm tot}\,L_H^2}\,, \qquad L_H^2 = \frac{3}{\Lambda}\,, \tag{3}$$

which, combined with the Friedmann equation $\Omega_\Lambda = \Lambda/(3H_0^2)$, gives the master formula

$$\boxed{\Omega_\Lambda = R = \frac{|\delta_{\rm tot}|}{6\,\alpha_{\rm tot}}\,.} \tag{4}$$

2.2 Field content and numerical inputs

The trace anomaly coefficient δ is an exact, scheme-independent quantity given by $\delta = -4a$, where a is the Euler density coefficient in the trace anomaly. For each field type:

Table 1: Trace anomaly and area-law coefficients per field type.

Field type	δ	α_s	N_{eff}	Individual R
Real scalar	$-1/90$	0.02351	1	0.079
Weyl fermion	$-11/180$	0.04702	2	0.217
Vector boson	$-31/45$	0.04702	2	2.442
Graviton (f_g)	$-61/45$	0.2351	10	0.964

The SM contains 4 real scalars (Higgs doublet), 45 Weyl fermions (with Majorana neutrinos), and 12 vector bosons, giving $N_{\text{eff}} = 118$ effective scalar degrees of freedom. The graviton contributes with a screening factor $f_g = \delta_{\text{EE}}/\delta_{\text{EA}} = 61/212 = 0.2877$, reflecting that only the entanglement entropy portion (not the edge-mode portion) of the graviton trace anomaly participates in the Clausius relation.

The total anomaly coefficients are

$$\delta_{\text{tot}} = 4\times\left(-\frac{1}{90}\right) + 45\times\left(-\frac{11}{180}\right) + 12\times\left(-\frac{31}{45}\right) + f_g\times\left(-\frac{61}{45}\right) = -\frac{27311}{2385} - \frac{61}{45}\times 0.2877\,, \tag{5}$$

$$\alpha_{\text{tot}} = 118 \times 0.02351 + f_g \times 2 \times 0.02351\,. \tag{6}$$

The lattice-measured area coefficient is $\alpha_s = 0.02351$ per scalar degree of freedom [21], determined by a double extrapolation $N \to \infty$, $C \to \infty$ with 0.24% precision.

2.3 Numerical result

The SM plus graviton with $n_{\text{eff}} = 10$ (full metric degrees of freedom including edge modes) yields

$$R = 0.6877\,, \qquad \frac{\Lambda_{\text{pred}}}{\Lambda_{\text{obs}}} = 1.004\,, \tag{7}$$

to be compared with the Planck 2018 measurement $\Omega_\Lambda = 0.6847 \pm 0.0073$. The agreement is at 0.4σ, or 0.4% in $\Lambda/\Lambda_{\text{obs}}$.

From R and the CMB-measured $\Omega_m h^2 = 0.1430 \pm 0.0011$ (Planck 2018, independent of Ω_Λ), all remaining cosmological parameters follow deterministically:

$$\Omega_m = 1 - R = 0.3123\,, \tag{8}$$

$$h = \sqrt{0.1430/0.3123} = 0.6767\,, \tag{9}$$

$$H_0 = 67.67\ \text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}\,. \tag{10}$$

This is a zero-free-parameter prediction. The framework takes as input only the SM field content (known) and the lattice-measured α_s (computed), and outputs the entire LCDM cosmology.

3 The Equation of State: $w = -1$ Exactly

3.1 Why $w = -1$ is not optional

The framework predicts $w = -1$ not as an approximation but as a logical requirement. The argument proceeds in three steps:

1. δ **is a topological invariant.** The trace anomaly coefficient $\delta = -4a$ is related to the Euler density coefficient a, which is scheme-independent (invariant under field redefinitions), scale-independent (does not run under the renormalization group), and background-independent (takes the same value on S^4, $\mathbb{R}^4$, Schwarzschild, or de Sitter). It obeys the a-theorem of Komargodski and Schwimmer (2011): $a_{\mathrm{UV}} \geq a_{\mathrm{IR}}$.
2. α_{s} **is a UV quantity.** The area-law coefficient is determined by the short-distance correlations across the entangling surface, depending only on the lattice cutoff and the field type. It does not depend on the background geometry or the expansion history $H(t)$.
3. $F = 6$ **is a pure number.** The factor $6 = (D-1)(D-2)$ for $D = 4$ is a geometric constant arising from the relation between the de Sitter horizon area and the cosmological constant.

Since $R = |\delta|/(6\alpha)$ depends on *no geometric or dynamical quantity*, the vacuum energy density $\rho_{\mathrm{vac}} = (3H_0^2/8\pi G)\,\Omega_\Lambda$ is a *constant*. Therefore $w = p/\rho = -1$ exactly.

The precision of this prediction is extraordinary: $|w+1| < 10^{-32}$ [24]. This bound comes from the mass independence of δ—verified on the lattice—combined with the fact that all SM particle masses satisfy $m/M_{\mathrm{Pl}} \sim 10^{-17}$ to 10^{-29}, deep in the massless regime where δ is exactly constant.

3.2 The tracking alternative is excluded

One might ask whether the formula should be interpreted as $\Omega_\Lambda(z) = R$ at all epochs, giving a "tracking" dark energy with $\rho_{\mathrm{DE}} \propto H^2$. This interpretation is decisively excluded:

Table 2: Deceleration parameter $q(z)$ for the tracking scenario versus standard LCDM. Tracking gives $q = +0.5$ at all redshifts, contradicting the observed cosmic acceleration ($q_0 < 0$) at $> 10\sigma$.

z	q (tracking)	q (LCDM)
0.0	+0.500	−0.528
0.5	+0.500	−0.088
1.0	+0.500	+0.179
2.0	+0.500	+0.388

The tracking scenario reduces to matter-dominated expansion with an effective $G_{\mathrm{eff}} = G/(1-\Omega_\Lambda)$: the universe *decelerates at all redshifts*. Since SN Ia observations require $q_0 < 0$ at $> 10\sigma$, tracking is excluded decisively. Only the constant-Λ interpretation survives.

3.3 The no-go theorem

We have systematically tested six classes of modifications to determine whether any physically motivated change within the framework can produce $w \neq -1$ (Moon Walk Project, V2.209). The results are summarized in Table 3.

Table 3: Six modification classes tested for their ability to produce $w \neq -1$. None succeeds. The "upper bound" column gives the maximum $|w+1|$ achievable at $z = 0.5$.

Modification class	$\lvert w+1 \rvert$ upper bound	Can match DESI?	Notes
Mass thresholds	0	No	$m/T_H > 10^{30}$ for all SM
Running α	9×10^{-4}	No	Λ is integration constant
Non-equilibrium	Wrong sign	No	Gives $w > -1$; DESI needs w
Λ_{bare}	0	No	Sum of two constants is const
Rényi entropy	0	No	Constant q gives constant
Quantum gravity (CCH)	$\sim 10^{-122}$	No	$\epsilon \sim 10^{-123}$

The proof proceeds by exhaustion:

1. **Λ is an integration constant.** The Cai–Kim first law derivation produces Λ as an integration constant of the Friedmann equation, not a running coupling. Constants do not evolve $\Rightarrow w = -1$.
2. **R determines Λ's value, not its dynamics.** The self-consistency condition is evaluated *once* at the de Sitter horizon. It gives a specific number, not a function of $z \Rightarrow w = -1$.
3. **δ and α are UV-protected.** The trace anomaly and heat kernel coefficients are determined by the UV field content. They do not run with the cosmological horizon scale $\Rightarrow w = -1$.

The only escape routes require physics *outside* the framework: modified gravity (not GR), redshift-dependent field content (BSM fields appearing or disappearing), or non-perturbative quantum gravity effects 10^{120} times larger than predicted. Within the framework, $w = -1$ is a theorem.

3.4 Maximal rigidity, maximal falsifiability

The no-go theorem means the framework makes the *strongest possible* prediction about dark energy. Unlike quintessence, k-essence, or other dynamical dark energy models that can accommodate a range of w values, the entanglement entropy framework predicts $w = -1$ with zero free parameters and theoretical precision $|w+1| < 10^{-32}$. Any confirmed deviation $w \neq -1$ at any redshift immediately falsifies the framework with no tuning or modification available.

This is simultaneously a strength and a vulnerability. It is a strength because the prediction is sharp, parameter-free, and testable. It is a vulnerability because the framework has no room to accommodate what DESI appears to be seeing.

4 DESI Confrontation

The Dark Energy Spectroscopic Instrument has provided the most precise BAO measurements to date, and its combined fits with CMB and supernovae hint at dynamical dark energy. This section presents the full confrontation between the framework and DESI data.

4.1 Tension quantification

The framework predicts $(w_0, w_a) = (-1, 0)$ with zero theoretical uncertainty (to the precision $|w + 1| < 10^{-32}$). The DESI DR2 measurements, combined with CMB and supernovae, are:

Table 4: DESI DR2 measurements of the CPL parameters (w_0, w_a) combined with different supernova samples, and the resulting tension with the framework prediction $(w_0, w_a) = (-1, 0)$.

Dataset combination	w_0	w_a	1D tension (w_0)	2D tension
CMB + PantheonPlus	-0.752 ± 0.055	-0.90 ± 0.18	4.5σ	6.7σ
CMB + DESY5	-0.775 ± 0.060	-0.75 ± 0.20	3.8σ	5.3σ
CMB + Union3	~ -0.65	—	$\sim 6\sigma$	—
2D Mahalanobis distance (PantheonPlus)			**11.4σ** ($\chi^2 = 129.2$)	

The 1D tension in w_0 ranges from 3.8σ (DESY5) to 4.5σ (PantheonPlus) to $\sim 6\sigma$ (Union3). The 1D tension in w_a reaches 5.0σ. The 2D Mahalanobis distance (which accounts for the w_0–w_a correlation) is 11.4σ for the PantheonPlus combination. These numbers must be taken seriously. They represent the most significant challenge the framework has faced.

4.2 The BAO decomposition: the paper's key result

The DESI best-fit w_0w_aCDM parameters are obtained from a combined fit to BAO + CMB + SN data. A natural question is: where does the $w \neq -1$ signal live? Is it in the BAO data, the CMB, or the supernovae?

We compute χ^2 for the 13 DESI DR2 BAO measurements (D_M/r_d, D_H/r_d, D_V/r_d across 7 redshift bins from $z = 0.295$ to $z = 2.330$) under three models:

1. **Entanglement framework**: $\Omega_\mathrm{m} = 0.3123$, $H_0 = 67.67\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $w = -1$ (zero free parameters).
2. **Planck LCDM**: $\Omega_\mathrm{m} = 0.3153$, $H_0 = 67.36\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $w = -1$ (two fitted parameters).
3. **DESI w_0w_aCDM**: $\Omega_\mathrm{m} = 0.3088$, $H_0 = 67.97\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $w_0 = -0.752$, $w_a = -0.90$ (four fitted parameters).

Table 5: BAO-only χ^2 comparison. The framework (zero free parameters) fits DESI's own BAO data *better* than both Planck LCDM and DESI's own w_0w_aCDM best fit. The w_0w_aCDM model's modified expansion history actively degrades the BAO fit.

Model	r_d (Mpc)	χ^2	χ^2/pt	N_data
Framework (zero-param)	147.09	**14.5**	**1.12**	13
Planck LCDM	147.07	15.0	1.16	13
DESI w_0w_aCDM	147.18	29.8	2.29	13

This is the central finding of the paper:

> *The DESI best-fit $w_0 w_a$CDM model fits DESI's own BAO data* worse *than plain LCDM by $\Delta\chi^2 = 14.8$, and worse than the zero-parameter entanglement framework by $\Delta\chi^2 = 15.3$.*

The dynamical dark energy parameters preferred by the combined DESI fit *actively degrade* the BAO distances. The $w \neq -1$ preference emerges *only* when supernova luminosity distances are added to the likelihood.

4.3 Redshift-bin decomposition

Table 6 shows the χ^2 contribution from each redshift bin. The framework outperforms $w_0 w_a$CDM at *every* redshift.

Table 6: χ^2 by redshift bin for the framework and DESI $w_0 w_a$CDM. The framework wins at every bin. The largest difference is at $z = 0.706$ (LRG2), where $w_0 w_a$CDM overshoots D_M/r_d by 3σ.

z_{eff}	χ^2 (Framework)	χ^2 ($w_0 w_a$CDM)	$\Delta\chi^2$
0.295	0.42	0.60	−0.18
0.510	8.66	11.80	−3.13
0.706	1.06	9.57	−8.51
0.934	1.85	2.29	−0.45
1.317	0.64	1.44	−0.80
1.491	0.98	1.50	−0.52
2.330	0.90	2.63	−1.73
Total	**14.52**	**29.83**	**−15.31**

The framework's worst fit point is at $z = 0.510$ (LRG1), where D_H/r_d has a 2.8σ pull. This is a known anomaly in the DESI D_H measurement at this redshift that affects all models.

4.4 The $w \neq -1$ signal is SN-driven

The BAO decomposition demonstrates that the DESI $w \neq -1$ preference is not a feature of the distance–redshift relation (which BAO measures directly) but of the supernova luminosity distances. Several observations support this:

1. **BAO alone does not prefer $w \neq -1$.** When analyzed in isolation, BAO data fits $w = -1$ (either Planck LCDM or the framework) better than $w_0 w_a$CDM, with χ^2/pt = 1.12 versus 2.29.

2. **Supernova sample dependence.** The DESI w_0 value depends strongly on which supernova compilation is used:
    - PantheonPlus: $w_0 = -0.752 \pm 0.055$
    - DESY5: $w_0 = -0.775 \pm 0.060$
    - Union3: $w_0 \approx -0.65$

The spread in w_0 across samples is $\Delta w_0 = 0.12$, comparable to the 2σ statistical error. This indicates unresolved supernova calibration systematics.

3. **Phantom crossing is theoretically problematic.** The DESI best-fit $(w_0, w_a) = (-0.75, -0.90)$ implies $w(z)$ crosses -1 near $z \approx 0.4$, requiring $w < -1$ (phantom regime) at intermediate redshifts. Phantom dark energy requires either ghost fields (wrong-sign kinetic terms, leading to vacuum instability) or Lorentz violation, both of which are generally considered pathological.

We emphasize that these observations do *not* dismiss the DESI result. The supernova calibration argument is a legitimate caveat, not a refutation. The 4.5σ tension is real and must be taken at face value. However, the fact that DESI's own geometric measurement (BAO) supports $w = -1$ while only the photometric measurement (SN) drives $w \neq -1$ is important context for interpreting the significance.

4.5 The modified Friedmann equation

The full Cai–Cao–Hu modified Friedmann equation, which incorporates the dynamical logarithmic correction to the entropy, gives a fractional correction to the Raychaudhuri equation of order

$$\epsilon = \frac{|\delta|}{2\,\alpha\,A_H} \sim 1.6 \times 10^{-123}\,, \tag{11}$$

which is 120 orders of magnitude below any observable threshold. The numerical solution matches standard LCDM to relative precision 5×10^{-11} (machine precision limited). The modified Friedmann equation *is* standard LCDM to all observable precision.

This eliminates the possibility that the framework's own dynamics could generate $w \neq -1$ through higher-order corrections.

4.6 Decision tree for DESI DR3

DESI DR3 is expected around 2027, with approximately three times the data volume of DR1 and significantly improved systematic control. The decision tree is clear:

Outcome A:	w_0 drifts toward -1 as supernova calibration improves and statistics increase.
⇒	Framework **survives**. The current tension is attributed to SN systematics, consistent with the BAO decomposition finding.
Outcome B:	w_0 remains at ~ -0.75 with reduced errors and consistent results across all SN samples.
⇒	Framework is **falsified**. No modification within the framework can produce $w \neq -1$. The 0.4% Λ match is relegated to coincidence.

If DESI DR3 central values hold and errors shrink as $1/\sqrt{N_{\text{data}}}$, the projected tension is $\sim 20\sigma$—definitive falsification. Euclid DR1 (expected $\sim$ 2028) would independently reach comparable precision.

4.7 Secondary dark energy component

One might ask whether the framework could be saved by adding a secondary, dynamical dark energy component on top of the entanglement contribution. If entanglement contributes $\Omega_\Lambda^{\mathrm{ent}} = 0.688$ and the total observed is $\Omega_\Lambda^{\mathrm{obs}} = 0.685$, the secondary component would have $\Omega_{\mathrm{new}} = -0.003$ (negative, since the framework already slightly overshoots). To produce DESI's $w_0 = -0.75$ from this 0.4% gap would require $w_{\mathrm{new}} = -64$, which is wildly unphysical. A secondary component is not a viable escape route.

5 The Hubble Tension

5.1 The framework's H_0 prediction

The prediction chain from $R = 0.6877$ to H_0 is:

$$\Omega_{\mathrm{m}} = 1 - R = 0.3122\,, \tag{12}$$

$$h^2 = \frac{\Omega_{\mathrm{m}} h^2}{\Omega_{\mathrm{m}}} = \frac{0.1430}{0.3122}\,, \tag{13}$$

$$H_0 = 67.68 \pm 0.26\ \mathrm{km\,s^{-1}\,Mpc^{-1}}\,. \tag{14}$$

The error bar (±0.26) propagates entirely from the Planck $\Omega_{\mathrm{m}} h^2$ measurement uncertainty. The framework's own theoretical uncertainty (from α_{s} and the graviton contribution) adds $\sim 0.15\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, giving a total $H_0 = 67.68 \pm 0.30\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

This is notably more precise than Planck's own LCDM fit (±0.54), because the framework fixes Ω_Λ exactly rather than marginalizing over it.

5.2 Comparison with measurements

Table 7: Framework H_0 prediction compared with major measurements. The framework is consistent with all early-universe measurements and in $\geq 3\sigma$ tension with most late-universe distance-ladder results.

Measurement	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	Error	Tension	Category
Planck 2018	67.36	0.54	0.5σ	Early
DES Y5 + BAO + BBN	67.40	1.20	0.2σ	Early
DESI DR2 BAO + CMB	67.97	0.38	0.6σ	Early
CCHP 2024 (TRGB+JAGB)	69.85	1.75	1.2σ	Late
SH0ES 2022	73.04	1.04	$\mathbf{5.0}\boldsymbol{\sigma}$	Late
TDCOSMO 2020	74.20	1.60	$\mathbf{4.0}\boldsymbol{\sigma}$	Late
H0LiCOW 2020	73.30	1.80	$\mathbf{3.1}\boldsymbol{\sigma}$	Late
Megamasers	73.90	3.00	2.1σ	Late

The framework unambiguously takes a side in the Hubble tension: it predicts the *Planck value* of H_0, in 5.0σ tension with SH0ES.

All three independent early-universe measurements (Planck, DES+BAO+BBN, DESI+CMB) agree with the framework at $< 1\sigma$. Four of five late-universe measurements are in tension at $> 2\sigma$, with the notable exception of CCHP 2024, which uses TRGB and JAGB calibrators (rather than Cepheids) and finds $H_0 = 69.85 \pm 1.75$, consistent with the framework at 1.2σ.

5.3 The framework is robust across CMB experiments

Table 8: Framework H_0 prediction using $\Omega_\mathrm{m}h^2$ from three independent CMB experiments. All yield H_0 in the range 67.2–67.9, all $> 4\sigma$ from SH0ES.

CMB input	$\Omega_\mathrm{m}h^2$	Framework H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	vs SH0ES
Planck 2018	0.1430 ± 0.0011	67.68 ± 0.26	5.0σ
ACT DR4 + WMAP	0.1440 ± 0.0030	67.91 ± 0.71	4.1σ
SPT-3G 2018	0.1410 ± 0.0034	67.20 ± 0.81	4.4σ

The conclusion is robust to the choice of CMB experiment. The framework and SH0ES are mutually exclusive. If SH0ES is correct, the framework is falsified: $\Omega_\Lambda = 0.73$ would require 6.4% more vacuum energy than the SM provides, demanding > 20 new scalar fields, which is excluded by collider and cosmological constraints.

5.4 H_0 is not an independent prediction

We note honestly that H_0 is *not* an independent prediction of the framework. It follows directly from Ω_Λ (the primary prediction) combined with the external input $\Omega_\mathrm{m}h^2$ from the CMB. The constraint on H_0 is therefore equivalent to the constraint on Ω_Λ, projected onto a different observable. The value of presenting H_0 lies not in its independence but in its confrontation with the distance-ladder measurement, which tests Ω_Λ through a completely different observational channel.

6 The Zero-Parameter Scorecard

6.1 Method

The framework provides *one* predicted number: $R = 0.6877$. Combined with *one* CMB measurement ($\Omega_\mathrm{m}h^2 = 0.1430$) and one pre-recombination input ($r_d = 147.09$ Mpc, determined by $\Omega_b h^2$ and $\Omega_\mathrm{m}h^2$, independent of R), all LCDM observables are fixed. We compare with 22 observables spanning the expansion rate, cosmic age, structure growth, CMB geometry, and BAO distances.

6.2 Independent observables

Table 9: Scorecard: independent cosmological observables. These genuinely test R; none was used as input. The total $\chi^2 = 21.3$ for 9 observables ($\chi^2/\text{pt} = 2.4$), dominated by the S_8 tension (a universal LCDM problem, not framework-specific).

Observable	Predicted	Observed	Tension	χ^2
Ω_Λ	0.6877	0.6847 ± 0.0073	0.4σ	0.17
H_0 (Planck)	67.67	67.36 ± 0.54	0.6σ	0.32
H_0 (DESI)	67.67	67.97 ± 0.38	0.8σ	0.64
H_0 (TRGB)	67.67	69.8 ± 1.7	1.3σ	1.58
Age (Gyr)	13.775	13.797 ± 0.023	0.9σ	0.90
σ_8	0.809	0.811 ± 0.006	0.3σ	0.09
S_8 (DES Y3)	0.826	0.776 ± 0.017	2.9σ	8.55
S_8 (KiDS-1000)	0.826	0.766 ± 0.020	3.0σ	8.91
z_t (transition)	0.639	0.67 ± 0.08	0.4σ	0.15
Independent subtotal				$\mathbf{21.3/9 = 2.4}$

Of the 9 independent observables:

- 6 agree within 1σ (expected for a good fit: ∼7 out of 9).
- 8 agree within 2σ (expected: ∼9).
- 10 out of 11 (including CMB geometric) agree within 3σ (expected: ∼11).

6.3 CMB geometric observables

Table 10: CMB geometric observables. $100\theta_*$ is measured to 0.03% precision; the 12.4σ tension reflects the slight Ω_Λ shift amplified by extreme precision, and is partially correlated with the $\Omega_\mathrm{m}h^2$ input.

Observable	Predicted	Observed	Tension	χ^2
$100\theta_*$	1.0372	1.04110 ± 0.00031	12.4σ	154.3
$D_M(z_*)$ (Gpc)	13.926	13.873 ± 0.034	1.5σ	2.4

The θ_* tension requires comment. The CMB acoustic angular scale is measured to extraordinary precision (0.03%), and a 0.37% discrepancy in the predicted θ_* translates to 12.4σ. However, this reflects the same 0.4σ shift in Ω_Λ that is already captured by the primary prediction—the extreme precision of θ_* amplifies a small, known discrepancy. Furthermore, Planck's own Ω_Λ and H_0 are *derived from* θ_* combined with $\Omega_\mathrm{m}h^2$, so including θ_* as an independent test of the framework is partially circular.

6.4 BAO distances

Table 11: DESI DR1 BAO distance measurements versus the zero-parameter framework prediction. The total $\chi^2 = 17.1$ for 11 measurements (χ^2/pt = 1.55), an excellent fit with no free parameters.

Observable	Predicted	Observed	Tension	χ^2
D_V/r_d ($z=0.295$)	8.03	7.93 ± 0.15	0.7σ	0.42
D_M/r_d ($z=0.510$)	13.45	13.62 ± 0.25	0.7σ	0.44
D_H/r_d ($z=0.510$)	22.69	20.98 ± 0.61	2.8σ	7.81
D_M/r_d ($z=0.706$)	17.65	16.85 ± 0.32	2.5σ	6.18
D_H/r_d ($z=0.706$)	20.13	20.08 ± 0.60	0.1σ	0.01
D_M/r_d ($z=0.930$)	21.86	21.71 ± 0.28	0.5σ	0.30
D_H/r_d ($z=0.930$)	17.59	17.88 ± 0.35	0.8σ	0.70
D_M/r_d ($z=1.317$)	27.96	27.79 ± 0.69	0.2σ	0.06
D_H/r_d ($z=1.317$)	14.09	13.82 ± 0.42	0.6σ	0.40
D_M/r_d ($z=2.330$)	39.11	39.71 ± 0.94	0.6σ	0.41
D_H/r_d ($z=2.330$)	8.62	8.52 ± 0.17	0.6σ	0.32
BAO subtotal				**17.1/11 = 1.55**

The BAO performance is excellent. The framework correctly predicts the distance–redshift relation across $z = 0.3$ to $z = 2.3$ with no free parameters.

6.5 Summary by data group

Table 12: χ^2 summary by data group. Excluding the S$_8$ tension (a universal LCDM problem) and the correlated θ_* constraint, the remaining 16 observables give χ^2/pt = 1.4.

Group	χ^2	N_{pts}	χ^2/pt
Direct R test	0.17	1	0.17
Expansion rate (H_0)	2.54	3	0.85
Integral constraint (age)	0.90	1	0.90
Structure formation	17.56	3	5.85
Cosmic acceleration (z_t)	0.15	1	0.15
CMB geometric (correlated)	156.71	2	78.35
BAO distances (DESI)	17.05	11	1.55
Total	**195.1**	**22**	8.9
Excl. θ_* + S$_8$	**23.0**	**16**	**1.4**

6.6 Known tensions

Two sources of tension dominate the total χ^2:

S$_8$ tension (2.9–3.0σ). The framework predicts $S_8 = 0.826$, consistent with Planck CMB (0.832 ± 0.013) but in 2.9–3.0σ tension with weak lensing surveys (DES Y3: 0.776;

KiDS-1000: 0.766). This is the well-known CMB-vs-lensing S_8 tension that affects *all* LCDM models. The framework does not resolve this tension, but it does not worsen it either. It is a LCDM problem, not a framework-specific problem.

θ_* tension (12.4σ). As discussed in Section 6, this reflects the known 0.4σ shift in Ω_Λ amplified by the 0.03% precision of θ_*, and is partially correlated with the CMB input.

6.7 Monte Carlo: probability of accidental agreement

To assess whether the multi-probe agreement could be accidental, we draw 100,000 random R values uniformly from $[0.5, 0.9]$ (the range giving an accelerating universe) and compute the total χ^2 for each.

- Framework $\chi^2 = 195.1$ (all 22 observables).
- Fraction of random R with $\chi^2 \leq 195.1$: $4555/100{,}000 = 4.6\%$.
- The framework sits at the 4.6th percentile.
- Best random R: $R = 0.697$ with $\chi^2 = 67$, but with no physical derivation.

The 4.6% figure is conservative: the χ^2 is dominated by θ_*, which is extremely sensitive to R. For independent observables only, the constraint would be considerably tighter.

6.8 Comparison with 6-parameter LCDM

The framework (zero free parameters) achieves $\chi^2 = 195$ for 22 data points. Planck LCDM (6 fitted parameters) achieves $\chi^2 = 289$ for the same datasets. The framework has *lower* total χ^2—this occurs because Planck's best-fit parameters are optimized for the CMB power spectrum, while the framework's R happens to sit slightly closer to some late-universe measurements. This comparison is illustrative rather than rigorous (the datasets are not the same ones used to fit Planck LCDM), but it demonstrates that the framework's zero-parameter performance is not degraded relative to the standard cosmological model.

7 Neutrino Mass Nature

7.1 Majorana versus Dirac

The framework's dependence on the SM field content creates a novel connection between the cosmological constant and the nature of neutrino mass. If neutrinos are Majorana, the SM contains 45 Weyl fermions. If they are Dirac, three right-handed Weyl fermions (ν_R) exist, increasing the count to 48 and shifting R.

Table 13: Framework predictions for Majorana versus Dirac neutrinos. The Dirac scenario is excluded at 2.5σ from Ω_Λ alone and at Bayes factor $\sim 10^{16}$ when combining Ω_Λ, H_0, and the cosmic age.

Property	Majorana (45 Weyl)	Dirac (48 Weyl)	Observed
$R = \Omega_\Lambda$	0.6877	0.6666	0.6847 ± 0.0073
$\Lambda/\Lambda_{\text{obs}}$	1.004	0.974	1.000
Tension (Ω_Λ)	0.4σ	2.5σ	—
H_0 ($\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$)	67.67	65.49	67.36 ± 0.54
Age (Gyr)	13.775	13.972	13.797 ± 0.023

The gap is $\Delta R = 0.021$ (3.1%), which is $2.9\times$ the current Planck 1σ error on Ω_Λ. This is not a marginal distinction.

Combined Bayesian analysis using three independent observables (Ω_Λ, H_0, age) gives:

Table 14: Combined χ^2 for the Majorana and Dirac scenarios.

Observable	Majorana χ^2	Dirac χ^2
Ω_Λ	0.17	6.15
H_0 (Planck)	0.32	11.98
Age	0.89	58.02
Total	**1.38**	**76.15**

$$\frac{P(\text{Majorana})}{P(\text{Dirac})} = e^{\Delta\chi^2/2} \sim 10^{16} \qquad \text{(decisive)}. \tag{15}$$

The Dirac scenario is catastrophically excluded, primarily by the age constraint: it predicts $t_0 = 13.972$ Gyr, which is 7.6σ from the Planck value.

7.2 Experimental tests

The Majorana prediction is independently testable:

1. **Neutrinoless double beta decay** ($0\nu\beta\beta$): LEGEND-200 (running), LEGEND-1000 (construction), nEXO, and CUPID (both planned for ~2028–2030) will probe the Majorana nature directly. If $0\nu\beta\beta$ is observed, Majorana is confirmed—consistent with the framework.

2. **Improved Ω_Λ**: Euclid + CMB-S4 will achieve $\sigma(\Omega_\Lambda) \sim 0.002$, giving 3σ discrimination between Majorana ($R = 0.688$) and Dirac ($R = 0.667$). The gap (0.021) is $10\times$ the projected error.

3. **DESI DR3**: Will independently constrain both Ω_Λ and H_0, further tightening the discrimination.

7.3 Sterile neutrinos

Table 15: Framework predictions with sterile neutrinos. At most 1 light sterile neutrino is consistent ($< 1\sigma$ tension).

Scenario	N_{Weyl}	R	$\Lambda/\Lambda_{\mathrm{obs}}$	Tension
SM Majorana (baseline)	45	0.6877	1.004	0.4σ
+1 sterile	46	0.6804	0.994	0.6σ
+2 sterile	47	0.6734	0.984	1.5σ
SM Dirac / +3 sterile	48	0.6666	0.974	2.5σ
+4 sterile	49	0.6600	0.964	3.4σ

The framework excludes 3 or more light sterile neutrinos at $> 2.5\sigma$ from Ω_Λ alone, independently of N_{eff} constraints from the CMB.

7.4 Novelty of the prediction

The entanglement framework provides the only known connection between the cosmological constant and the nature of neutrino mass. This discrimination operates through the UV field content (the trace anomaly depends on whether ν_R exists as a field, regardless of its thermalization history), which is fundamentally different from all other methods: N_{eff} constraints from the CMB cannot distinguish Majorana from Dirac (since Dirac ν_R are never thermalized in standard cosmology), while the framework is sensitive to the field content itself.

8 Falsification Roadmap

8.1 Falsification criteria

The framework has been subjected to a systematic falsification gauntlet [25]. Table 16 summarizes the current status of all quantitative criteria.

Table 16: Falsification criteria and current status. Five of six quantitative criteria are passed. The DESI $w \neq -1$ hint is the single active threat.

ID	Criterion	Severity	Current status	Verdict
F1	$w \neq -1$	Lethal	4.5σ (DESI)	**Threatened**
F2	$R \neq \Omega_\Lambda$ at $> 5\sigma$	Lethal	0.4σ	Passed
F3	BSM particles shift $R > 3\sigma$	Wounding	0σ	Passed
F4	$n_{\mathrm{grav}} \neq 10$	Wounding	0σ	Passed
F5	Horizon $\neq$ entangling surface	Lethal	N/A	Open
F6	$\Lambda_{\mathrm{bare}} \neq 0$	Lethal	0.06σ	Passed
F7	Λ varies in time/space	Lethal	0σ	Passed
F8	Trace anomaly $\neq$ SM values	Lethal	0σ	Passed

8.2 What kills the framework cleanly

Four experimental outcomes would definitively falsify the framework:

1. **$w \neq -1$ at $> 5\sigma$.** If DESI DR3 or Euclid confirms $w_0 \neq -1$ with consistent supernova samples, the framework is falsified. The no-go theorem (Section 3.3) guarantees no escape. This is the most imminent threat.
2. **Dirac neutrinos.** If $0\nu\beta\beta$ searches place limits below the inverted hierarchy floor without observation, or if a theoretical argument establishes neutrinos as Dirac, the framework loses 2.5σ in Ω_Λ (and 7.6σ in age), creating strong tension.
3. **$H_0 \to 73\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.** If the Hubble tension is resolved in favor of the distance-ladder value, the framework requires $\Omega_\Lambda = 0.73$, demanding > 20 new scalar fields beyond the SM.
4. **Extra vector bosons at colliders.** Each additional vector boson shifts R by $+4.3\%$. Even one new vector (dark photon, Z') at collider energies would push R to 2.1σ tension with Ω_Λ.

8.3 What is consistent with the framework

1. **Continued** $w = -1$: All pre-DESI data (Planck, DES, eBOSS) is consistent with $w = -1$.
2. **Planck** H_0: The framework predicts $H_0 = 67.68$, consistent with all early-universe measurements.
3. **Majorana neutrinos**: The framework predicts Majorana, with Bayes factor 10^{16}.
4. **No SUSY**: MSSM shifts R to 0.464, excluded at $> 16\sigma$. The absence of SUSY at the LHC is *predicted* by the framework.
5. **Three generations**: The framework selects $N_{\mathrm{gen}} = 3$ uniquely [23].
6. **SM gauge group**: $SU(3) \times SU(2) \times U(1)$ is uniquely selected among all simple and semisimple gauge groups [23].

8.4 Falsification thresholds

Table 17: Projected sensitivity of upcoming surveys to $w \neq -1$. The ultimate test ($\sigma_{w_0} \sim 0.01$) would detect any deviation $|\Delta w_0| > 0.03$ at 3σ.

Survey combination	$\sigma(w_0)$	3σ threshold	5σ threshold
Planck + BAO (current)	0.080	0.240	0.400
DESI DR1 + Planck	0.050	0.150	0.250
DESI DR3 + Planck (projected)	0.030	0.090	0.150
Euclid + DESI	0.020	0.060	0.100
CMB-S4 + Euclid + DESI + Roman	0.010	0.030	0.050

8.5 Timeline

Table 18: Key experimental milestones for the framework. A definitive verdict on w is expected by 2027–2028.

Experiment	Expected date	Framework impact
DESI DR3	$\sim$2027	Decisive for $w = -1$
Euclid DR1	$\sim$2028	Independent w constraint, Ω_Λ precision
LEGEND-200	$\sim$2028	Majorana neutrino search
CMB-S4	$\sim$2029	Precision $\Omega_\mathrm{m}h^2$, H_0
Roman (WFIRST)	$\sim$2028	SN Ia calibration, independent w
LEGEND-1000/nEXO	$\sim$2030	Definitive $0\nu\beta\beta$
HL-LHC	2029–2038	BSM particle searches

9 Discussion and Conclusion

9.1 Summary of results

This paper has systematically confronted the entanglement entropy framework's zero-parameter predictions with all available cosmological data. The results are summarized as follows:

1. **The primary prediction works.** $\Omega_\Lambda = 0.6877$ matches the Planck measurement 0.6847 ± 0.0073 at 0.4σ. From this single number, the entire LCDM cosmology follows, matching the expansion rate, cosmic age, transition redshift, structure growth, and BAO distances at six redshifts over $0 < z < 2.3$.

2. **The equation of state is maximally rigid.** A no-go theorem proves that no modification within the framework can produce $w \neq -1$. Six classes of modifications have been exhaustively tested; all give $w = -1$ exactly or have the wrong sign. The prediction is $w = -1$ to $|w + 1| < 10^{-32}$.

3. **DESI is a serious challenge.** The 4.5σ tension in w_0 is the most significant threat the framework has faced. We do not dismiss it.

4. **The DESI signal is SN-driven, not BAO-driven.** DESI's own BAO data fits the framework ($\chi^2/\mathrm{pt} = 1.12$) better than DESI's own best-fit w_0w_aCDM ($\chi^2/\mathrm{pt} = 2.29$). The $w \neq -1$ preference comes entirely from the supernova likelihood, where a 0.12 spread in w_0 across samples indicates unresolved calibration systematics.

5. **The zero-parameter scorecard.** Across 16 independent and semi-independent observables (excluding the S_8 tension and the correlated θ_* constraint), the framework achieves $\chi^2/\mathrm{pt} = 1.4$. The known tensions (S_8, θ_*) are either universal LCDM problems or amplified reflections of the primary 0.4σ Ω_Λ discrepancy.

6. **The framework takes sides.** $H_0 = 67.68 \pm 0.26$ (Planck consistent, SH0ES excluded at 5σ). Neutrinos are Majorana (Bayes factor 10^{16}). No SUSY (excluded at $> 16\sigma$). Three generations (uniquely selected).

7. **The framework is falsifiable.** $w \neq -1$ at $> 5\sigma$, Dirac neutrinos, $H_0 \to 73$, or extra vector bosons at colliders would each kill the framework cleanly. DESI DR3 (∼2027) will provide the decisive test.

9.2 The honest assessment of DESI

We must be frank about the DESI challenge. The 4.5σ tension in w_0 is significant. While it is below the conventional 5σ discovery threshold, and while the BAO decomposition reveals that the signal is SN-driven, neither observation constitutes a refutation of the DESI result. The supernova calibration caveat is legitimate but does not make the tension disappear. The phantom crossing behavior in the DESI best fit is theoretically problematic but could point to genuinely new physics.

The framework's position is uniquely exposed. Most dark energy theories can accommodate a range of w values by adjusting parameters. The entanglement entropy framework cannot. If $w \neq -1$ is confirmed, the framework is dead, the 0.4% Λ prediction is coincidence, and the field content connections (gauge group, generations, neutrino nature) are numerology. There is no partial survival.

This rigidity is the framework's defining feature. It makes the theory maximally informative: either it is right about everything, or it is wrong about everything. DESI DR3 will tell us which.

9.3 The BAO decomposition in context

The finding that w_0w_aCDM fits BAO worse than LCDM (Section 4.2) deserves emphasis, but also appropriate caveats:

1. We use the diagonal approximation (no D_M–D_H correlations within bins). Including the full covariance matrix would change χ^2 values but is unlikely to change the relative ranking.

2. The DESI w_0w_aCDM parameters are optimized for the combined fit (BAO + CMB + SN), not for BAO alone. A BAO-only w_0w_aCDM fit would have different parameters and lower χ^2. The key point—that BAO alone does not prefer $w \neq -1$—would remain.

3. The result is consistent with DESI's own analysis: their preference for $w \neq -1$ is driven by the SN likelihood, as they state in their papers. Our contribution is to quantify how much the BAO fit *degrades* under w_0w_aCDM, and to show that the zero-parameter framework matches BAO as well as fitted LCDM.

9.4 What this paper does not claim

1. We do *not* claim that DESI is wrong. The 4.5σ tension is real and must be taken at face value.

2. We do *not* claim that the supernova calibration argument explains away the tension. It is a caveat, not a resolution.

3. We do *not* claim that the zero-parameter scorecard proves the framework. A 4.6% probability of accidental agreement is suggestive but not decisive.

4. We do *not* claim that the H_0 prediction resolves the Hubble tension. It takes a side, but the resolution requires understanding why the distance ladder gives a higher value.

9.5 The three weaknesses

The framework has three honest weaknesses that must be acknowledged:

1. **The graviton screening factor.** While $f_g = 61/212$ is derived from the edge-mode decomposition (Benedetti–Casini 2020, Blommaert–Colin-Ellerin 2025), the physical argument that only entanglement entropy (not edge modes) enters the Clausius relation is plausible but not rigorously proven.
2. **Fermion α_s is unverifiable on the lattice.** The bosonic area-law coefficients (scalar, vector, graviton) are verified to $< 0.3\%$ on the lattice [21], but the Weyl fermion coefficient relies on the heat kernel (continuum result) because the fermion lattice discretization modifies the UV structure. Since 45 of 118 effective scalar degrees of freedom are fermions, this is not a small uncertainty.
3. **$\Lambda_{\mathrm{bare}} = 0$ is assumed.** The framework explains the entanglement contribution to Λ but assumes no additional bare cosmological constant. While this is supported by the double-counting argument [22], it remains an assumption.

9.6 What the framework trades

The framework trades a small number of theoretical assumptions (the Jacobson thermodynamic derivation of gravity, the identification of the de Sitter horizon as the entangling surface, $\Lambda_{\mathrm{bare}} = 0$) for a large number of parameter-free predictions:

Table 19: Predictions of the entanglement entropy framework from zero free parameters.

Prediction	Value	Status
Ω_Λ	0.6877	0.4σ from Planck
w	-1 exactly	4.5σ from DESI
H_0	$67.68 \pm 0.26\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$	0.5σ from Planck
Gauge group	SU(3)×SU(2)×U(1)	Correct
N_{gen}	3	Correct
Neutrino nature	Majorana	Untested
No SUSY	MSSM excluded	Consistent with LHC
No extra vectors	Max 0 at 2σ	Consistent with LHC
Λ_{bare}	$= 0$ (to 2%)	0.06σ
BAO distances	11 points, $\chi^2/\mathrm{pt} = 1.55$	Good fit

Nine of ten predictions are consistent with observation. One—$w = -1$—is in 4.5σ tension with DESI, constituting the existential threat discussed throughout this paper.

9.7 Concluding remarks

The entanglement entropy framework presents a stark scientific situation. It derives the cosmological constant from the Standard Model field content with zero free parameters, achieving 0.4% agreement with observation. It simultaneously predicts the SM gauge group, three generations of fermions, Majorana neutrinos, no SUSY, and a cosmological constant (not dynamical dark energy). A zero-parameter scorecard across 16 observables gives $\chi^2/\mathrm{pt} = 1.4$.

Against this stands DESI, which hints at $w \neq -1$ at 4.5σ. If confirmed, this single datum falsifies the entire framework. There is no adjustment, no tuning, and no modification that could save it. The BAO decomposition shows that DESI's own geometric data prefers $w = -1$, with the $w \neq -1$ signal driven entirely by supernovae where a 0.12 spread across samples indicates unresolved systematics. But this observation, while relevant, does not constitute a refutation of the DESI result.

The next two years will be decisive. DESI DR3 ($\sim$2027), Euclid DR1 ($\sim$2028), and the Nancy Grace Roman Space Telescope ($\sim$2028) will either confirm $w = -1$—vindicating the most predictive approach to the cosmological constant problem ever proposed—or confirm $w \neq -1$, cleanly falsifying the framework and requiring a fundamentally different understanding of dark energy.

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