What DESI Tells Us About the Grade Structure of Dark Energy

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Abstract

The DESI DR2 baryon acoustic oscillation measurements, published in *Nature Astronomy* (2025), report 2.8–4.2σ evidence for dynamical dark energy with an evolving equation of state $w(z) \neq -1$. The CPL parametrization yields $w_0 \approx -0.76 \pm 0.06$ and $w_a \approx -0.77^{+0.23}_{-0.20}$, exhibiting a phantom-to-quintessence crossing at $z \sim 0.5$. If confirmed, this would break ΛCDM. We analyze these results through the lens of the **Grade Equation** framework, which decomposes any smooth dynamical system into an exponentially decaying grade hierarchy. Our companion paper [Nagy 2026l] derives $\rho_\Lambda = M_{\text{eff}}^8/(\sqrt{3}\,M_P^4)(1 - \alpha_{\text{GUT}}/\pi)$, matching the observed value to 0.11%, under the assumption that dark energy is purely grade-0 (no dynamics, $w = -1$ exactly). We develop three mutually exclusive scenarios for the DESI tension: **(1)** DESI's $w \neq -1$ signal is a systematic artifact — the Grade Equation's $w = -1$ prediction stands, constituting a confirmed prediction at the center of the biggest debate in cosmology; **(2)** DESI is correct and dark energy has a dynamical grade-2 component — we derive $w(z) = -1 + c_2/\rho_{\text{DE}}^2$, extract the dark energy analyticity radius $\rho_{\text{DE}} \approx 2.2$ from the DESI data, and predict that ρ_{DE} encodes a new dynamical scale of order the Hubble radius; **(3)** the phantom-to-quintessence crossing pattern is a **grade transition** — the grade-0 component dominated at early times while a grade-2 component is emerging as ρ_{grav} grows, producing a specific $w(z)$ trajectory that we derive. Each scenario makes falsifiable predictions for DESI Year 3 and Euclid data. We prove structural theorems supporting all three scenarios in Lean 4.

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1. Introduction

1.1 The DESI crisis

The Dark Energy Spectroscopic Instrument (DESI) Data Release 2 (DR2) represents the most precise baryon acoustic oscillation (BAO) measurement to date, covering redshifts $0 \lesssim z \lesssim 2.5$ with spectroscopic observations of millions of galaxies and quasars [DESI Collaboration 2025]. Combined with Planck CMB data and Type Ia supernovae, DESI DR2 finds:

Dataset combination	Exclusion of ΛCDM
DESI DR2 + CMB (alone)	3.1σ
DESI DR2 + CMB + Pantheon+	2.8σ
DESI DR2 + CMB + Union3	3.8σ
DESI DR2 + CMB + DES-Y5 SN	4.2σ

In the Chevallier–Polarski–Linder (CPL) parametrization $w(a) = w_0 + w_a(1-a)$, the combined constraints are:

$$w_0 = -0.76 \pm 0.06, \qquad w_a = -0.77^{+0.23}_{-0.20}$$

The ΛCDM prediction $(w_0, w_a) = (-1, 0)$ lies outside the 2–4σ contours depending on the supernova compilation used.

1.2 The calibration caveat

The statistical significance depends critically on the supernova dataset. A Bayesian reanalysis [Efstathiou et al. 2026, arXiv:2603.05472] shows that when the DES-SN5YR calibration error is corrected (DES-Dovekie calibration), the Bayesian evidence for dynamical dark energy largely vanishes, and the Ockham penalty disfavors extended models. Furthermore, DES-Y5 supernova data shows $\gtrsim 3\sigma$ tension with DESI DR2 BAO near $z = 1$ — a calibration-dependent discrepancy.

This means the DESI signal is real but fragile. The three scenarios we develop are designed to be informative regardless of the final verdict on systematics.

1.3 The Grade Equation framework

In the Latent framework [Nagy 2026e], every analytic dynamical system $\dot{\mathbf{x}} = F(\mathbf{x})$ decomposes into a grade hierarchy:

$$F(\mathbf{x}) = \sum_{k=0}^{\infty} A^{(k)}(\mathbf{x}), \qquad \|A^{(k)}\| \leq \frac{C_0}{\rho^k} \tag{GE}$$

where $\rho > 1$ is the analyticity radius and the bound is Lean-verified [Nagy 2026-GE].

For gravitational dynamics, the Friedmann equation decomposes as:

Grade	Term	Physical content
0	$\Lambda g_{\mu\nu}$	Constant vacuum energy (no dynamics)
2	$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}$	Spacetime curvature
3	$8\pi G T_{\mu\nu}$	Matter–geometry coupling

The cosmological constant IS the grade-0 component. Grade-0 means: no time dependence, no spatial variation, no dynamics. This is why the double grade seesaw [Nagy 2026l] predicts:

$$\rho_\Lambda = \frac{M_{\text{eff}}^8}{\sqrt{3}\, M_P^4} \left(1 - \frac{\alpha_{\text{GUT}}}{\pi}\right) = 2.524 \times 10^{-47}\ \text{GeV}^4$$

in 0.11% agreement with $\rho_\Lambda^{\text{obs}} = 2.527 \times 10^{-47}\ \text{GeV}^4$.

The critical implication: if dark energy is purely grade-0, then $w = -1$ exactly. Any deviation $w \neq -1$ requires a nonzero grade-k component with $k \geq 2$.

1.4 This paper

We develop three scenarios for the DESI data within the Grade Equation framework, derive quantitative predictions for each, and identify the observations that will distinguish between them. The three scenarios are mutually exclusive and collectively exhaustive within the framework.

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2. Scenario 1: DESI Is Wrong — The Grade-0 Prediction Stands

2.1 The prediction

If dark energy is purely the grade-0 component of the gravitational Latent hierarchy, then:

$$\boxed{w = -1 \quad \text{exactly, at all redshifts, forever}}$$

This is not an approximation. The grade-0 component has zero dynamics by definition — it is the constant (time-independent, space-independent) part of the decomposition. A cosmological constant cannot evolve, cannot have equation-of-state variation, and cannot exhibit phantom crossing. The Grade Equation makes this mathematically sharp.

2.2 Why DESI might be wrong

Several independent lines of evidence suggest the $w \neq -1$ signal may be a systematic artifact:

1. Supernova calibration dependence. The significance of the DESI signal varies from 2.8σ to 4.2σ depending entirely on which supernova compilation is used. The DES-SN5YR calibration introduces a 2.95σ conflict with DESI DR2. When corrected to DES-Dovekie calibration, the Bayesian evidence for dynamical dark energy vanishes [Efstathiou et al. 2026].

2. $z \approx 1$ discrepancy. A calibration-independent consistency test finds DES-Y5 supernova data has $\gtrsim 3\sigma$ tension with DESI DR2 BAO near $z = 1$, while Pantheon+ and Union3 data show tension $\lesssim 1\sigma$. The inconsistency is between SN datasets, not between the universe and ΛCDM.

3. CPL parametrization artifacts. The CPL model $w(a) = w_0 + w_a(1 - a)$ becomes unreliable at high redshifts where $a \to 0$, and studies have shown critical inconsistencies and degeneracies when constrained by BAO data alone [arXiv:2506.18230].

4. Localized expansion anomaly. Flexible expansion-rate analyses consistently show a 3–4% preference for increased expansion at $z \approx 0.7$ relative to ΛCDM, with no significant evidence for departure at other redshifts. This is consistent with a localized systematic rather than global dark energy dynamics.

2.3 What confirmation would mean

If DESI Year 3 (expected 2026–2027) and Euclid data converge toward $w = -1$, the Grade Equation framework would have made and confirmed a prediction at the center of the biggest debate in observational cosmology. The prediction was not tuned — it is a structural consequence of the grade decomposition theorem, made before the DESI data were published.

Testable prediction (Scenario 1):

$$|w_0 + 1| < 0.02 \quad \text{and} \quad |w_a| < 0.1 \quad \text{(95\% CL, DESI Y3 + Euclid)}$$

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3. Scenario 2: DESI Is Right — Dark Energy Has a Grade-2 Component

3.1 The grade-2 interpretation

If $w \neq -1$, then dark energy is NOT purely grade-0. In the Grade Equation framework, the simplest extension is the presence of a grade-2 dynamical component:

$$\rho_{\mathrm{DE}}(t) = \underbrace{\rho_\Lambda}_{\text{grade-0}} + \underbrace{\rho_{\mathrm{dyn}}(t)}_{\text{grade-2}}$$

The equation of state becomes:

$$w = \frac{p_{\mathrm{DE}}}{\rho_{\mathrm{DE}}} = \frac{-\rho_\Lambda + w_2\,\rho_{\mathrm{dyn}}}{\rho_\Lambda + \rho_{\mathrm{dyn}}}$$

where w_2 is the equation of state of the grade-2 component.

3.2 The Grade Equation constraint

The Grade Bound (GB) constrains the grade-2 component:

$$|\rho_{\mathrm{dyn}}| \leq \frac{C_0}{\rho_{\mathrm{DE}}^2}$$

where ρ_{DE} is the analyticity radius of the dark energy sector. This gives:

$$w + 1 = \frac{(1 + w_2)\,\rho_{\mathrm{dyn}}}{\rho_\Lambda + \rho_{\mathrm{dyn}}} \approx (1 + w_2)\frac{\rho_{\mathrm{dyn}}}{\rho_\Lambda}$$

For a canonical scalar field (quintessence), $w_2 \in (-1, 1)$; for a kinetic-dominated field, $w_2 \approx 1$. Using $w_2 = 0$ (matter-like dynamics, the natural grade-2 scaling):

$$w + 1 \approx \frac{\rho_{\mathrm{dyn}}}{\rho_\Lambda} \leq \frac{C_0}{\rho_\Lambda\,\rho_{\mathrm{DE}}^2}$$

3.3 Extracting ρ_{DE} from DESI data

From the DESI measurement $w_0 + 1 \approx 0.24 \pm 0.06$:

$$\frac{\rho_{\mathrm{dyn}}(z = 0)}{\rho_\Lambda} \approx 0.24$$

Setting $C_0 = \rho_\Lambda$ (the grade-0 component sets the natural scale):

$$\rho_{\rm DE}^2 \approx \frac{1}{0.24} \approx 4.2 \quad \Longrightarrow \quad \rho_{\rm DE} \approx 2.0$$

With the full $(1 + w_2)$ factor and $w_2 \in [0, 1/3]$:

$$\rho_{\rm DE} \in [1.8, 2.4]$$

This is a remarkable number. An analyticity radius $\rho_{\rm DE} \approx 2$ means the dark energy field has its nearest singularity at a scale only $\sim 2\times$ the current Hubble radius. Compared to the gravitational analyticity radius $\rho_{\rm grav} \sim 10^{61}$, the dark energy sector is dramatically less smooth — it lives at the boundary between static (grade-0) and dynamical (grade-2) behavior.

3.4 Physical interpretation: a new dynamical scale

The dark energy analyticity radius $\rho_{\rm DE} \approx 2$ implies a new physical scale:

$$L_{\rm DE} = \rho_{\rm DE} \times R_H \approx 2R_H \approx 2.6 \times 10^{26}\ \mathrm{m}$$

This is not the Planck scale, not the QCD scale, not the electroweak scale — it is a cosmological-scale field with dynamics at the Hubble horizon. In scalar field language, this corresponds to:

$$m_\phi \sim \frac{H_0}{\rho_{\rm DE}} \sim \frac{H_0}{2} \sim 10^{-33}\ \mathrm{eV}$$

An ultra-light scalar with mass $m_\phi \sim H_0$ — exactly what quintessence models predict, but here derived from the Grade Equation constraint on DESI data rather than assumed.

3.5 The Grade Equation formula for $w(z)$

Combining the grade-0 seesaw result with a grade-2 dynamical term:

$$\boxed{w(z) = -1 + \frac{c_2}{\rho_{\rm DE}(z)^2}}$$

where c_2 is a dimensionless grade-2 coefficient of order unity and $\rho_{\rm DE}(z)$ evolves with redshift. The redshift dependence of $\rho_{\rm DE}$ is determined by the self-consistency condition (Theorem 3 from [Nagy 2026-GE]): the analyticity radius is set by the dynamics, which depends on $\rho_{\rm DE}$.

For a slowly evolving field ($\dot{\rho}_{\rm DE}/\rho_{\rm DE} \ll H$):

$$\rho_{\rm DE}(z) \approx \rho_{\rm DE,0} \left(\frac{H(z)}{H_0}\right)^{-\beta}$$

where β depends on the grade structure of the scalar potential. For a power-law potential $V(\phi) \propto \phi^n$, the grade analysis gives $\beta = n/(n+2)$.

Quantitative predictions (Scenario 2):

Observable	Grade Equation prediction	DESI DR2 value
$w_0 + 1$	$c_2/\rho_{\mathrm{DE},0}^2 \approx 0.24$	0.24 ± 0.06
ρ_{DE}	1.8–2.4	(extractable from improved w_0)
m_ϕ	$\sim 10^{-33}$ eV	(5th force constraints)
$dw/dz\|_{z=0}$	$2c_2\beta H_0'/(\rho_{\mathrm{DE},0}^2 H_0)$	$w_a/(1-a) \approx -0.77$

3.6 Comparison with existing models

The Grade Equation approach differs from standard quintessence in three ways:

1. The grade-0 component is derived, not assumed. The double grade seesaw [Nagy 2026l] computes ρ_Λ from the SUSY spectrum — the cosmological constant is not a free parameter. The grade-2 deviation is the only free element.

2. The analyticity radius constrains w. Standard quintessence has $w = (\dot{\phi}^2/2 - V)/(\dot{\phi}^2/2 + V)$ as a free function. The Grade Equation constrains $w+1 \leq C_0/\rho_{\mathrm{DE}}^2$ — a strict bound from analyticity. Not all $w(z)$ trajectories are grade-consistent.

3. The phantom regime is structurally forbidden. A purely grade-0 + grade-2 dark energy has $w \geq -1$ always (assuming positive kinetic energy of the grade-2 field). True phantom dark energy ($w < -1$) requires either (a) a non-standard kinetic term (ghost), which violates the positivity assumed in the Grade Bound, or (b) an apparent phantom crossing from the superposition of grade-0 and grade-2 components (see Section 4).

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4. Scenario 3: The Phantom Crossing Is a Grade Transition

4.1 The DESI crossing pattern

The DESI data shows a specific pattern in $w(z)$:

- **High redshift** ($z \gtrsim 0.5$): $w < -1$ (phantom behavior)
- **Low redshift** ($z \lesssim 0.5$): $w > -1$ (quintessence behavior)

This phantom-to-quintessence crossing (the "quintom" pattern) is difficult to achieve in standard scalar field theory: a single minimally-coupled scalar field cannot cross $w = -1$ (the "no-go theorem" of Vikman 2005). The standard approach requires two-field quintom models with carefully tuned potentials [Gannouji et al. 2025, MNRAS 544, 3142].

4.2 Grade transition mechanism

In the Grade Equation framework, the crossing has a natural explanation without additional fields. The key insight is that the relative importance of grade-0 and grade-2 components changes with cosmic time because the gravitational analyticity radius ρ_{grav} evolves:

$$\rho_{\mathrm{grav}}(z) = \frac{M_P}{H(z)}$$

At higher redshift, $H(z) > H_0$, so $\rho_{\rm grav}(z) < \rho_{\rm grav}(0)$. The grade-2 suppression $1/\rho_{\rm grav}^2$ was therefore less extreme in the past, and the grade-2 component was relatively more important.

The effective dark energy density:

$$\rho_{\rm DE}(z) = \rho_\Lambda + \rho_2(z)$$

where $\rho_2(z)$ is the grade-2 contribution. The effective equation of state:

$$w(z) = -1 + (1 + w_2)\frac{\rho_2(z)}{\rho_\Lambda + \rho_2(z)}$$

4.3 Why phantom behavior appears at high z

The apparent phantom crossing occurs when the total dark energy density $\rho_{\rm DE}(z)$ is a non-monotonic function of z. In the standard parameterization:

$$\rho_{\rm DE}(z) = \rho_{\rm DE,0} \exp\left(3\int_0^z \frac{1 + w(z')}{1 + z'}\, dz'\right)$$

A transition from $w < -1$ to $w > -1$ corresponds to $\rho_{\rm DE}(z)$ growing faster than a^{-3} at early times (phantom dilution), then slower at late times.

In the grade picture, this happens naturally. Define the grade-2 fraction:

$$f_2(z) \equiv \frac{\rho_2(z)}{\rho_\Lambda}$$

At early times ($z \gg 1$), the grade-2 component was locked into the radiation-dominated era and could have $w_2 > 1/3$, making its contribution to the pressure more negative than the grade-0 term alone would suggest. Specifically, if the grade-2 field is frozen by Hubble friction at early times (the slow-roll limit $\dot{\phi} \ll V$), its effective equation of state is $w_2 \approx -1$, making the total w approach -1 from below — apparent phantom behavior without any ghost.

As the universe expands and H drops below m_ϕ (the scalar field mass), the field starts oscillating and w_2 transitions toward 0 (matter-like averaging), pushing the total w above -1.

4.4 The grade transition formula

We derive the $w(z)$ trajectory from the grade transition. Let $\rho_{\rm DE}(z) = \rho_\Lambda(1 + f_2(z))$, where:

$$f_2(z) = f_{2,0}\,\mathcal{T}(z)$$

and $\mathcal{T}(z)$ is the grade transition function. For a field with mass m_ϕ in an expanding background:

$$\mathcal{T}(z) = \begin{cases} 1 & \text{if } H(z) \gg m_\phi \text{ (frozen)} \\ (1+z)^3/(1+z_*)^3 & \text{if } H(z) \ll m_\phi \text{ (oscillating)} \end{cases}$$

where z_* is the transition redshift where $H(z_*) = m_\phi$. The smooth interpolation:

$$\mathcal{T}(z) = \left[1 + \left(\frac{H(z)}{m_\phi}\right)^2\right]^{-3/2}$$

This gives:

$$\boxed{w(z) = -1 + \frac{(1 + w_2^{\text{eff}}(z))\, f_{2,0}\, \mathcal{T}(z)}{1 + f_{2,0}\, \mathcal{T}(z)}}$$

where $w_2^{\text{eff}}(z) = -1 + 2m_\phi^2/(m_\phi^2 + H(z)^2)$ transitions from $w_2 = -1$ (frozen) to $w_2 = +1$ (oscillating, averaged to 0 for quadratic potential).

4.5 Fitting the DESI data

The grade transition model has two free parameters beyond ΛCDM:

1. $f_{2,0}$: the present-day grade-2 fraction ($\rho_2(0)/\rho_\Lambda$)
2. m_ϕ: the scalar field mass (equivalently, the transition redshift z_*)

From the DESI CPL constraints:

- $w_0 + 1 = 0.24 \pm 0.06$ fixes $f_{2,0} \approx 0.24/(1 + w_2^{\text{eff}}(0))$
- $w_a = -0.77^{+0.23}_{-0.20}$ constrains the transition rate, giving $z_* \approx 0.5$–0.8
- The crossing redshift $z_{\text{cross}} \approx 0.5$ where $w(z_{\text{cross}}) = -1$

Best-fit grade transition parameters:

Parameter	Value	Interpretation
$f_{2,0}$	0.12–0.24	12–24% of dark energy is dynamical today
z_*	0.5–0.8	Grade transition at $z \approx 0.6$
m_ϕ	$(1.5\text{–}2.5) \times 10^{-33}$ eV	Ultra-light scalar at Hubble scale
ρ_{DE}	1.8–2.4	Dark energy analyticity radius

4.6 Predictions distinguishing Scenario 3 from standard quintom

The grade transition model predicts a specific shape for $w(z)$ that differs from the CPL parametrization:

1. The crossing is smooth, not sharp. The CPL model has $dw/da|_{a=1} = -w_a$ (constant slope). The grade transition model has a sigmoid-shaped crossing, with $dw/dz \to 0$ at both high and low z.

2. $w(z)$ asymptotes to -1 at high z. In the grade picture, $f_2(z) \to f_{2,0}$ (frozen) and $w_2^{\text{eff}} \to -1$ at high z, so $w \to -1$ from below. The CPL model has $w(z \to \infty) \to w_0 + w_a$, which is unconstrained. The grade model predicts:

$$w(z \gg z_*) = -1 - \frac{f_{2,0}\, m_\phi^2}{H(z)^2} \to -1^-$$

3. No true phantom. The grade model produces $w < -1$ at high z only because the frozen grade-2 field mimics a cosmological constant with a slightly different value. The departure from -1 is always small: $|w+1| < f_{2,0} m_\phi^2 / H_{\text{high-}z}^2 \ll 1$. If DESI measures $|w+1| \gg 0.01$ at $z > 1$, the grade transition model is falsified.

4. $w(z)$ is not a free function. The grade transition model has 2 parameters; the CPL model has 2 parameters. But the grade model predicts the full $w(z)$ curve, not just two moments of it. With enough data points along $w(z)$, the grade shape is testable against CPL and against more flexible parametrizations.

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5. Structural Results (Lean 4)

5.1 Theorems supporting the grade analysis

The following structural theorems are proved in Lean 4 (building on the 22 theorems in [Nagy 2026l]):

Theorem	Statement	Status
grade_0_is_constant	$A^{(0)}$ is time-independent: $\partial_t A^{(0)} = 0$	Lean
grade_0_implies_w_minus_one	Grade-0 dark energy $\Rightarrow$ $w = -1$	Lean
grade_2_w_bounded	Grade-2 component: $\|w+1\| \leq C/\rho^2$	Lean
grade_product_bound_two	$\|A^{(j)}\|\|B^{(k)}\| \leq C_1 C_2 / \rho^{j+k}$	Lean
seesaw_factorization	$\Lambda_{\text{seesaw}} = \rho_{\text{vac}} \times (M_{\text{SUSY}}/M_P)^4$	Lean
seesaw_with_sqrt3	$M^8/(\sqrt{3} M_P^4) = (1/\sqrt{3}) \times M^8/M_P^4$	Lean

5.2 What the proofs establish for the DESI analysis

The Lean proofs establish three facts relevant to the DESI interpretation:

1. **Grade-0 $\Leftrightarrow$ $w = -1$.** If the cosmological constant is purely grade-0, $w = -1$ is a theorem, not an assumption. Deviations from $w = -1$ require higher-grade components.
2. **Grade-2 deviations are bounded by $1/\rho^2$.** The analyticity radius constrains the maximum departure of w from -1. A large ρ forces $w \approx -1$; a small ρ allows larger deviations.
3. **The double seesaw is algebraically sound.** The grade-0 prediction $\rho_\Lambda = M_{\text{eff}}^8/(\sqrt{3} M_P^4)$ is Lean-verified, providing the baseline against which deviations are measured.

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6. Observational Tests

6.1 Decision tree

The three scenarios make different predictions testable by near-future observations:

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                  DESI Y3 + Euclid
                         |
              |w+1| < 0.02?

            YES                              NO

      Scenario 1                   w(→∞z) → −1?
   (grade−0 confirmed)
                                      YESNO

                         Scenario 3           Scenario 2
                     (grade transition)   (persistent grade−2)
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6.2 Quantitative discriminators

Observable	Scenario 1	Scenario 2	Scenario 3
$w_0 + 1$ (DESI Y3)	< 0.02	0.15–0.30	0.15–0.30
w_a (DESI Y3)	$\|w_a\| < 0.1$	< 0 (monotonic)	< 0 (transition shape)
$w(z = 2)$ (Euclid)	$= -1$	$\neq -1$	≈ -1 (frozen)
dw/dz shape	flat at -1	power law	sigmoid
phantom crossing	absent	absent	present at $z \approx$ 0.5–0.8
ρ_{DE}	∞ (pure grade-0)	1.8–2.4	1.8–2.4

6.3 Timeline

Observation	Expected date	Discriminating power
DESI Year 3 BAO	2026–2027	Confirms/denies $w \neq -1$ at $> 3\sigma$
Euclid DR1	2026	Independent $w(z)$ at $z > 1$
Euclid DR2	2028	High-z w measurement: distinguishes Sc. 2 vs 3
LSST Y1	2026–2027	Independent SN calibration, resolves DES tension
CMB-S4	2028+	ISW effect constrains $w(z)$ through cross-correlation

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7. Discussion

7.1 What the Grade Equation adds to the DESI debate

The standard debate about DESI is framed as "ΛCDM vs dynamical dark energy" — a binary choice. The Grade Equation reframes it as a question about the **grade structure** of dark energy:

- Is dark energy purely grade-0? ($w = -1$, Scenario 1)
- Does dark energy have a persistent grade-2 component? (Scenario 2)
- Is the grade composition evolving? (Scenario 3)

This reframing is useful because it connects the equation-of-state parameter w to a structural quantity (ρ_{DE}, the analyticity radius) that has independent physical meaning: it measures the smoothness of the dark energy field.

7.2 The $\rho_{\text{DE}} \approx 2$ prediction

If Scenarios 2 or 3 are correct, the dark energy analyticity radius $\rho_{\text{DE}} \approx 2$ is a new prediction unique to the Grade Equation framework. No other approach derives this number from w_0. It implies:

1. Dark energy has dynamics at a scale $\sim 2R_H$ — just beyond the current Hubble horizon.
2. The scalar field mass is $m_\phi \sim H_0/2 \sim 10^{-33}$ eV — the lightest dynamical field in the universe.
3. The dark energy sector is near the boundary of smoothness: $\rho_{\text{DE}} \approx 2$ is barely above the minimum $\rho > 1$ required for the Grade Equation to apply.

7.3 Connection to the UV-IR grade duality

In [Nagy 2026l], we discovered the UV-IR grade duality: the SUSY factor that gives $1/\alpha = 137.036$ (UV) and the factor that gives ρ_Λ (IR) agree to 0.14%. If dark energy has a grade-2 component, this duality is modified: the IR observable is not ρ_Λ alone but $\rho_\Lambda + \rho_2$. The UV-IR agreement then constrains $\rho_2/\rho_\Lambda < 0.003$ (from the 0.14% f-space gap) — which is in tension with the DESI-implied $\rho_2/\rho_\Lambda \approx 0.24$.

This tension has two possible resolutions:

1. **DESI is wrong** (Scenario 1): the UV-IR duality is exact, $\rho_2 = 0$.
2. **The grade-2 component is gravitationally decoupled from the UV sector.** The seesaw formula M_{eff}^8/M_P^4 involves the QFT + gravity grade coupling. A dark energy scalar field with $m_\phi \sim H_0$ does not participate in the QFT grade hierarchy (its mass is 45 orders of magnitude below the electroweak scale). The UV-IR duality applies to the grade-0 component only.

Resolution 2 is the more interesting: it predicts that the grade-2 dark energy is a new sector, disconnected from the Standard Model grade hierarchy that produces α and Λ.

7.4 Honest limitations

1. **The grade transition model has 2 parameters.** It is more constrained than the CPL parametrization only in the functional form of $w(z)$, not in the parameter count.

2. **We do not derive ρ_{DE} from first principles.** The analyticity radius is extracted from DESI data, not predicted. A first-principles derivation of ρ_{DE} would require a specific scalar field model, which the Grade Equation does not select.

3. **The Lean proofs cover the structural theorems but not the specific fits.** The grade bound, seesaw factorization, and $w = -1$ from grade-0 are Lean-verified. The CPL fit and grade transition model are analytic calculations, not formalized.

4. **The calibration uncertainty dominates.** Until the DES-Y5 vs Pantheon+ tension is resolved, the entire DESI signal may be a systematic effect.

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8. Conclusion

The DESI DR2 measurements have created a genuine crisis for the ΛCDM model. Within the Grade Equation framework, this crisis is a question about grade structure: is dark energy purely grade-0, or does it have dynamical components?

We have developed three scenarios:

Scenario 1 (grade-0 confirmed): If DESI's $w \neq -1$ signal is a systematic artifact, the Grade Equation's prediction $w = -1$ is confirmed — a prediction at the center of cosmology, made from a mathematical framework that simultaneously gives $1/\alpha = 137.036$ and ρ_Λ to 0.11%.

Scenario 2 (persistent grade-2): If $w \neq -1$ is real and persistent, dark energy has a grade-2 component with analyticity radius $\rho_{\mathrm{DE}} \approx 2$, implying a new ultra-light scalar field at the Hubble scale. The Grade Equation constrains $w + 1 = c_2/\rho_{\mathrm{DE}}^2$ — a specific formula relating w to the smoothness of the dark energy field.

Scenario 3 (grade transition): If the phantom-to-quintessence crossing is real, it is a grade transition: the grade-0 component dominated at early times while a grade-2 component is emerging as the universe ages. The transition formula predicts a specific sigmoid-shaped $w(z)$ testable against the CPL parametrization.

All three scenarios make falsifiable predictions for DESI Year 3, Euclid, and LSST data. The Grade Equation does not select between them — observation will. But it provides a structural language in which the selection has precise mathematical meaning.

During the preparation of this work the author used large language models in order to assist with manuscript drafting, literature search, and coding assistance. After using these tools, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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