

Holographic Dark Energy from Fundamental Principles to Precision Observations

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ABSTRACT

Holographic dark energy remains one of the few late universe frameworks in which the observed acceleration is tied directly to an ultraviolet and infrared consistency condition inspired by quantum gravity. The last five years have transformed the subject. The central question is no longer whether a holographic density can reproduce an accelerating background. Many constructions can do so. The decisive questions are whether the infrared prescription has a local theoretical completion, whether perturbations are stable and observationally acceptable, whether entropy deformations introduce physically meaningful freedom rather than flexible curve fitting, and whether the model survives the rapidly tightening combination of DESI baryon acoustic oscillations, supernova distances, cosmic microwave background information, cosmic chronometers, and growth measurements. This review critically synthesizes these developments with particular emphasis on the standard future event horizon model, interacting models, Barrow, Tsallis, Kaniadakis, Rényi and fractional extensions, local Ricci and Granda Oliveros cutoffs, effective field theory descriptions, nonflat cosmology, and recent data driven reconstructions. A striking empirical pattern emerges. Late time combinations can place the standard holographic parameter c close to unity or above unity, whereas the addition of cosmic microwave background information commonly drives c to values near 0.65 to 0.70 and therefore toward a phantom future. In DESI DR1 analyses the associated Bayesian evidence can strongly favor Λ CDM even when a holographic fit is acceptable in likelihood. DESI DR2 late time analyses again recover c close to unity, which sharpens rather than removes the dataset dependence. Generalized entropy models display a similarly mixed picture. Some constructions constrain deformation parameters close to their standard entropy limit, while others prefer large deformations but remain statistically disfavoured by Bayesian evidence. Structure growth calculations further show that infrared cutoff choice can determine viability. We argue that future progress requires perturbation complete models, consistent treatment of early and late universe information, explicit evidence calculations, and model comparison at the level of physically distinct cutoff and entropy prescriptions rather than broad labels. Holographic dark energy therefore remains theoretically

fertile, but current observations do not yet establish it as a superior replacement for Λ CDM.

1 Introduction

The cosmological constant remains the simplest description of the observed late universe acceleration, yet its microscopic interpretation is incomplete. Holographic dark energy approaches the problem from a different direction. It assumes that an effective quantum field theory cannot assign independent ultraviolet degrees of freedom to an arbitrarily large spatial region without eventually counting states whose total energy would exceed the mass of a black hole of the same size. The resulting energy bound links a short distance cutoff to a cosmological infrared scale. Cohen, Kaplan, and Nelson expressed the essential inequality as an energy restriction on an effective field theory [1]. Li then showed that choosing the future event horizon as the infrared scale produces a dark energy component with a dynamically evolving equation of state [2]. The mature pre DESI literature established the broad phenomenology, theoretical questions, and parameter degeneracies of this framework [3].

What has changed since 2021 is the standard of evidence. Background acceleration alone is no longer a sufficient criterion. A viable model must fit distance measurements over a long redshift lever arm, remain compatible with early universe calibration, possess a controlled perturbation sector, avoid pathologies that arise only after the background fit is obtained, and justify every additional parameter through predictive gain. These requirements are particularly demanding for holographic models because the infrared scale is part of the dynamics. A future event horizon is nonlocal in its usual representation. A Hubble or Ricci scale is local but can alter the ability of the model to accelerate or to reproduce structure. An entropy deformation adds theoretical motivation but also introduces another parameter whose observational meaning depends on the exact construction.

This review focuses on the five year research interval from 2021 through September 2026. Foundational papers are cited only where they are necessary to define the theoretical architecture. The recent literature is organized around five questions. The first is which infrared cutoff is physically and observationally viable. The second is whether energy exchange between dark matter and dark energy solves a real problem without creating new perturbative conflicts. The third is whether generalized horizon entropy leads to observable departures that survive statistical model selection. The fourth is whether local effective field theory, growth data, and stability considerations support the background phenomenology. The fifth is how the conclusions change when DESI measurements are combined with competing supernova compilations and cosmic microwave background information.

A critical distinction runs throughout the review. Parameter constraints answer where a model can fit the data. Information criteria and Bayesian evidence ask whether the improvement in fit compensates for the added freedom. Internal dataset consistency asks a third question, namely whether the same parameter region is selected by late and early universe information. A model may perform well under one criterion and poorly under another. Recent holographic dark energy results provide several clear examples, especially in the behavior of the standard parameter c and in generalized entropy fits.

Current architecture of holographic dark energy models

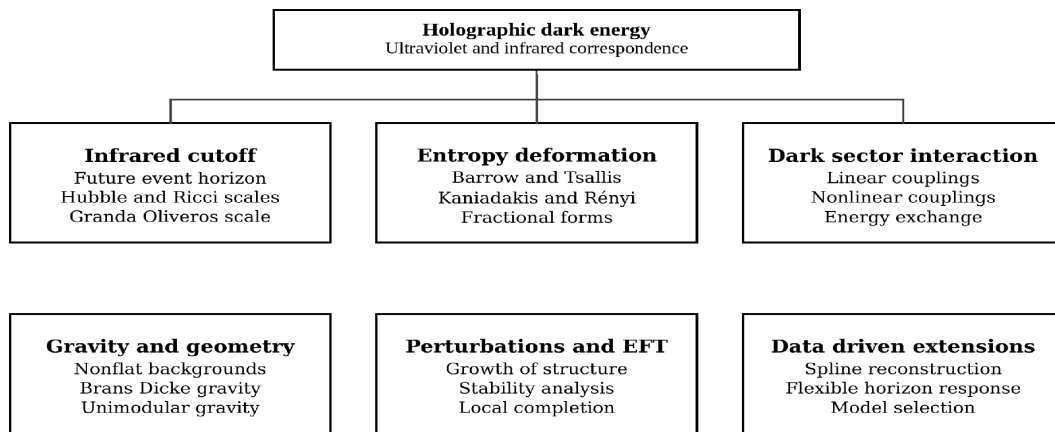


Figure 1. Original conceptual map prepared for this review. The recent literature can be organized by the infrared cutoff, entropy prescription, dark sector interaction, gravity and geometry, perturbation completion, and data driven reconstruction. No previously published artwork is reproduced.

2 Holographic foundation and the standard future event horizon model

The field theoretic energy bound may be written schematically as

$$L^3 \rho_\Lambda \leq LM_p^2 \quad 1$$

where L is the infrared length, M_p is the reduced Planck mass, and ρ_Λ represents the vacuum energy density associated with the ultraviolet cutoff. Saturating the bound gives the standard holographic form

$$\rho_{de} = 3c^2 M_p^2 L^{-2} \quad 2$$

The dimensionless constant c absorbs uncertainties in the saturation relation and in the precise mapping between the effective field theory bound and cosmology. Its importance is unusually direct. In the standard flat model with the future event horizon, c largely determines the late time equation of state and therefore the fate of the universe.

For the future event horizon prescription the infrared length is

$$L = a(t) \int_t^\infty \frac{dt'}{a(t')} \quad 3$$

This choice produces acceleration without inserting a cosmological constant by hand. In a matter plus dark energy background the fractional dark energy density obeys

$$\frac{d\Omega_{de}}{d\ln a} = \Omega_{de} \left(1 - \Omega_{de} \right) \left(1 + \frac{2\sqrt{\Omega_{de}}}{c} \right) \quad 4$$

and the equation of state becomes

$$w_{de} = -\frac{1}{3} - \frac{2\sqrt{\Omega_{de}}}{3c} \quad 5$$

These expressions expose the central role of c . As Ω_{de} approaches unity, c greater than one tends toward a quintessence like asymptote, c equal to one approaches the de Sitter boundary, and c less than one becomes phantom. The precise redshift of any crossing depends on the evolving Ω_{de} . The standard model is therefore highly predictive once c and the present matter density are specified, but it can also become vulnerable when different data combinations select incompatible values of c .

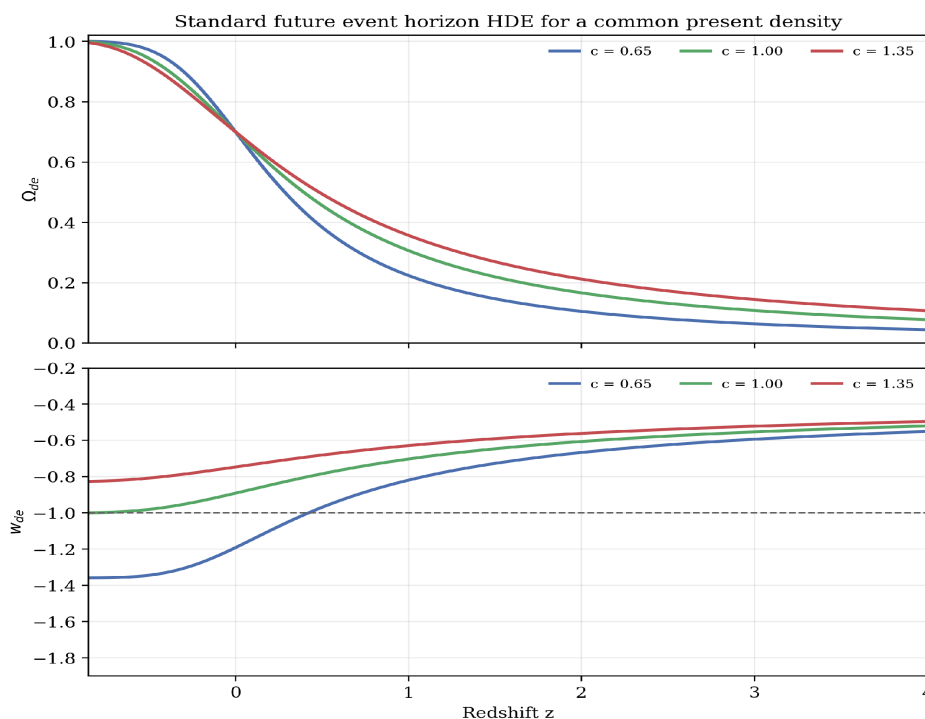


Figure 2. Original numerical integration of the standard flat future event horizon model with Ω_{de} at the present epoch fixed to 0.70. The upper panel shows the dark energy fraction. The lower panel shows the equation of state. The curves illustrate why the observational location of c relative to unity has a direct interpretation for the cosmic future. The calculation uses Eqs. 4 and 5 and reproduces no journal figure.

2.1 The nonlocality problem and local alternatives

The future event horizon has always generated a conceptual objection because its usual definition refers to the future expansion history. The practical evolution equations are well posed once appropriate boundary information is supplied, and earlier work showed that the apparent causality paradox can be reformulated in terms of boundary data rather than a literal transmission of information from the future. Even so, recent work has increasingly asked whether a local completion can make the model conceptually sharper. Two established local alternatives remain important. The Granda Oliveros cutoff uses a combination of H^2 and the

time derivative of H [4]. The Ricci prescription relates the infrared scale to curvature and can therefore avoid explicit dependence on a future boundary [5]. These choices are not merely formal rearrangements. They alter the background equations, perturbations, and the mapping between model parameters and observations.

The strongest theoretical development in the review period is the construction of a covariant effective field theory for holographic dark energy. Lin showed that the low energy description can be written as a massive gravity theory with two tensor polarizations and one scalar mode, with the scalar strong coupling scale providing a concrete ultraviolet and infrared interpretation [6]. Ganz and Lin then studied structure formation in this framework [7]. In the small scale limit, cold matter perturbations can follow the general relativistic form in the quintessence regime. The effective theory becomes problematic in a phantom regime because the scalar sector loses control. Removing the unstable scalar degree of freedom through an additional Hamiltonian constraint can restore stability, but the price can be a modified effective gravitational coupling or a nonzero sound speed for the matter component. This result is central to the modern assessment of holographic dark energy. A background fit that prefers c below unity is not automatically a theoretically complete success.

3 Infrared cutoff choice as the primary model discriminator

A major lesson of the last five years is that the phrase holographic dark energy hides models with qualitatively different physics. The infrared cutoff determines whether the dark energy density reacts to a global horizon, the instantaneous Hubble scale, a curvature scalar, or a derivative combination of the expansion rate. The choice controls not only acceleration but also parameter degeneracy, the response to early universe priors, and growth of structure. It should therefore be treated as a primary model definition rather than as a secondary technical choice.

The nonflat Barrow analysis of Adhikary and collaborators showed how curvature and a generalized horizon entropy can be combined consistently while retaining an event horizon construction [8]. Subsequent studies of Kaniadakis and Tsallis models also adopted the future event horizon and obtained rich background behavior [9, 10, 11]. By contrast, Landim tested interacting holographic dark energy with the Hubble scale cutoff and found that parameter values able to generate background acceleration produced matter and cosmic microwave background power spectra with shapes far from observation [12]. This is an instructive negative result. A mechanism that helps the coincidence problem at background level can fail decisively once perturbations are included.

Local derivative cutoffs continue to attract attention because they avoid an explicit future horizon. Oliveros, Sabogal, and Acero studied Barrow holographic dark energy with the Granda Oliveros scale and obtained a best fit deformation consistent with the standard entropy limit, $\Delta = 0.000$ with a positive one sigma uncertainty of about 0.004, using expansion rate data [13]. In a Brans Dicke setting, Ghaffari, Luciano, and Capozziello demonstrated that the same entropy modification can be embedded in a varying gravitational coupling framework [14]. Rudra proposed a Ricci cubic construction in which local curvature invariants define the cutoff [15]. These studies expand the theoretical design space, but they also make clear that observational statements about a named entropy model are not portable across different cutoff and gravity prescriptions.

Table 1. Model architecture and the principal physical issue associated with each class.

Model class	Infrared or entropy choice	New freedom	Principal strength	Principal risk
Standard HDE	Future event horizon	C	Minimal one parameter dynamics	Nonlocal representation and phantom fate for c below one
Hubble scale IHDE	Hubble radius with interaction	c and coupling	Can link coincidence and energy exchange	Perturbation spectra can fail
Granda Oliveros HDE	H^2 and time derivative of H	α and β	Local expansion based cutoff	Greater parameter degeneracy
Ricci HDE	Curvature based scale	Ricci parameter	Local geometric prescription	Early and late data can be inconsistent
Barrow HDE	Deformed horizon area law	Δ	Quantum geometry motivation	Constraints depend strongly on implementation
Tsallis HDE	Nonextensive entropy scaling	Δ	Flexible generalized thermodynamics	Cutoff dependence of growth
Kaniadakis HDE	Relativistic entropy deformation	K	Smooth standard entropy limit	Data often favor weak deformation

Model class	Infrared or entropy choice	New freedom	Principal strength	Principal risk
Rényi and fractional HDE	Alternative generalized entropy	entropy parameter	Broadens theoretical tests	Observational maturity remains limited

4 Generalized entropy holographic dark energy

The rapid growth of generalized entropy models is the most visible theoretical trend of the review period. Their common motivation is that the Bekenstein-Hawking area law may receive corrections from quantum geometry, nonextensive statistical mechanics, relativistic statistical theory, or fractional constructions. The resulting dark energy density generally changes its power-law dependence on the infrared scale or acquires additional nonlinear terms. The physical promise is that a deformation parameter may encode microscopic information. The statistical danger is that the same parameter can become a flexible degree of freedom that only absorbs residual disagreement among datasets.

4.1 Barrow holographic dark energy

Barrow entropy replaces the smooth horizon area by a fractal-inspired deformation. A common representation is

$$S_B \propto A^{1+\frac{\Delta}{2}} \quad 6$$

where Δ measures departure from the standard area law. The 2021 nonflat study showed that curvature and Barrow deformation can jointly alter the dark energy evolution [8]. Later Granda-Oliveros studies found that expansion data can drive Δ very close to zero [13]. A broader 2024 analysis by Yarahmadi and Salehi, including cosmic microwave background, baryon acoustic oscillations, cosmic chronometers, supernovae, lensing, and neutrino mass freedom, reported $\Delta = 0.0055 \pm 0.0086$ together with $\alpha = 0.997 \pm 0.060$ and $\beta = 0.598 \pm 0.080$ [16]. The same analysis reported $H_0 = 70.43 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for its broad data combination and a reduced discrepancy relative to both Planck and the adopted local measurement. This result is important but should not be generalized to all Barrow constructions because the cutoff, neutrino sector, and parameter freedom are integral parts of the fit.

4.2 Tsallis holographic dark energy

Tsallis holographic dark energy typically modifies the scaling of the energy density to a form proportional to L raised to a power controlled by the nonextensivity parameter. Pandey and collaborators developed a new future event horizon realization in 2022 and showed that the

standard thermal sequence and accelerated phase can be reproduced [11]. Perturbation work by Astashenok and Tepliakov later emphasized that holographic dark energy cannot always be treated as an ordinary local fluid because its boundary origin complicates the interpretation of standard perturbation prescriptions [17]. This observation is especially relevant when background likelihoods are used without a consistent perturbation implementation.

The 2025 observational analysis by Astashenok and Tepliakov used PantheonPlus, DESI 2024 baryon acoustic oscillations, Hubble measurements, and matter fluctuation information to constrain future event horizon Tsallis holographic dark energy [18]. A separate and more general entropy comparison by Cimdiker, Dabrowski, and Salzano found that generalized models based on standard, Rényi, Sharma Mittal, and Kaniadakis entropies were all substantially disfavoured relative to Λ CDM, with log Bayes factors around -14.7 in their setup, while the Barrow family was less strongly but still clearly disfavoured with a value around -6 [19]. Their Barrow analysis favored Δ greater than about 0.86 in that particular construction. This large value is in obvious tension with the near zero deformation found in Granda Oliveros analyses. The discrepancy is not necessarily a contradiction. The models use different mappings from entropy to energy density and different parameterizations. It demonstrates why generalized entropy constraints must always be quoted together with the cutoff and construction that produced them.

4.3 Kaniadakis holographic dark energy

Kaniadakis entropy is motivated by relativistic statistical mechanics and introduces a deformation parameter K that reduces continuously to the standard entropy expression when K tends to zero. Drepanou and collaborators showed in 2022 that the corresponding event horizon model can pass through quintessence, phantom, or phantom crossing regimes depending on its parameters, while the transition to acceleration typically occurs near redshift 0.6 [9]. Hernández Almada and collaborators confronted the model with cosmic chronometers, supernovae, and baryon acoustic oscillations and found the Kaniadakis parameter centered near the standard entropy limit. Their reconstructed deceleration transition was $z_T = 0.86$ with an upper uncertainty of 0.21 and a lower uncertainty of 0.14 [10].

The late time analysis by Luciano and Paliathanasis revisited the model with modern supernova, chronometer, and DESI information [20]. Representative combinations gave c close to unity. For PantheonPlus, baryon acoustic oscillations, and observational Hubble data they obtained H_0 near $68.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and c near 1.03 , while the Kaniadakis deformation was limited from above in the adopted parameterization. Their information criteria generally continued to favor Λ CDM. The combined message from the 2022 and 2025 studies is therefore conservative. Kaniadakis entropy can generate distinctive background trajectories, but present late time data do not require a substantial departure from the standard entropy limit.

4.4 Rényi, Sharma Mittal, and fractional constructions

Rényi and Sharma Mittal models have been studied as alternative nonextensive deformations, usually with the future event horizon. In the unified 2025 analysis they tracked standard holographic dark energy closely when the additional entropy parameters were small, and they did not overcome the Bayesian preference for Λ CDM [19]. A new Rényi realization proposed by Tamri and collaborators in 2026 again illustrates active theoretical development, with a logarithmic entropy deformation that smoothly recovers standard HDE [21]. Fractional holographic dark energy has also been reconstructed in scalar and gauge field languages by Bidlan, Moniz, and Trivedi [22]. These studies are valuable for mapping theoretical

correspondences, but the observational maturity of these newer constructions remains behind that of standard HDE, Barrow HDE, and the more widely tested Tsallis and Kaniadakis models.

Table 2. Selected numerical constraints in generalized entropy holographic dark energy. Parameter definitions are model specific and should not be compared without the stated construction.

Model and construction	Data or study	Key numerical result	Interpretation
Barrow with Granda Oliveros	Expansion rate fit [13]	$\Delta = 0.000$ with upper one sigma uncertainty 0.004	Standard entropy limit favored
Barrow with Granda Oliveros	Broad CMB plus late time fit [16]	$\Delta = 0.0055 \pm 0.0086$, $\alpha = 0.997 \pm 0.060$, $\beta = 0.598 \pm 0.080$	Small deformation in this construction
Kaniadakis event horizon	CC plus SNe plus BAO [10]	$z_T = 0.86$ with $+0.21$ and -0.14 uncertainty	Viable acceleration with K near zero
General entropy comparison	Combined cosmological data [19]	$\ln B$ about -14.7 for standard, Rényi, Sharma Mittal, and Kaniadakis HDE	Strong evidence penalty relative to Λ CDM
Barrow in general entropy comparison	Combined cosmological data [19]	$\ln B$ about -6 and Δ greater than about 0.86	Construction favors a large deformation but remains disfavoured

Model and construction	Data or study	Key numerical result	Interpretation
Kaniadakis late time fit	PantheonPlus plus BAO plus OHD [20]	H0 about 68.0 km s ⁻¹ Mpc ⁻¹ and c about 1.03	No compelling late time evidence for large deformation

5 Interacting holographic dark energy

An interaction between dark matter and holographic dark energy is attractive for two reasons. It can change the late time attractor and may reduce the coincidence problem, and it can alter the effective equation of state so that a phantom background does not necessarily imply the same future singularity as a noninteracting model. The background continuity equations are commonly written as

$$\dot{\rho}_{dm} + 3H\rho_{dm} = Q \quad 7$$

$$\dot{\rho}_{de} + 3H(1 + w_{de})\rho_{de} = -Q \quad 8$$

where Q specifies the direction and strength of energy transfer. The difficulty is that there is no unique interaction law. Common choices make Q proportional to H times one density, the total dark sector density, or a nonlinear combination. Every extra interaction form is a distinct physical model and can carry different perturbative behavior.

Landim provided a particularly important warning by testing several interactions when the Hubble radius is used as the cutoff. Although interaction can enable an effective nonzero dark energy equation of state in that setup, the predicted matter power spectrum and cosmic microwave background spectra were far from the observed shapes for the investigated parameter space [12]. This is a strong example of why a successful background coincidence mechanism cannot be judged independently of perturbations.

The observational picture is more nuanced for event horizon interaction. Li and collaborators revisited standard and interacting HDE after DESI DR1 [23]. Their interacting model preferred a positive coupling when CMB, DESI, and supernova data were combined, with representative coupling values near 0.55 in their parameterization and significance above three standard deviations. At the same time, Bayesian evidence still favored Λ CDM, even though interaction softened part of the evidence penalty relative to standard HDE. Shen and collaborators later examined ten interaction forms with DESI DR2, DES five year supernovae, Planck information, observational Hubble data, and a local H0 measurement [24]. They found that interaction can improve HDE relative to the noninteracting version, but Λ CDM remained the best supported model overall. This pattern suggests that interaction can be phenomenologically useful without yet being empirically required.

Nonflat interacting analyses add another layer. Shen and collaborators reported strong curvature preferences within their HDE and IHDE fits using a specific combined dataset [25]. Such results should be interpreted cautiously because curvature, c , the interaction strength, and H_0 are highly correlated in these models. A preference for nonzero curvature inside an extended holographic parameter space is not equivalent to a model independent detection of cosmic curvature. The result is better viewed as evidence that curvature can absorb some of the same discrepancies otherwise carried by c or Q .

6 Observational constraints in the DESI era

6.1 The new data landscape

The observational environment changed rapidly during the review period. PantheonPlus assembled 1701 light curves from 1550 Type Ia supernovae over redshifts from about 0.001 to 2.26 and provided a substantially enlarged late universe distance sample [26]. The Dark Energy Survey five year supernova program supplied an independent high precision compilation [27]. DESI DR1 then delivered baryon acoustic oscillation measurements over a broad redshift interval using several million extragalactic objects [28]. The Union3 compilation later combined 2087 cosmologically useful supernovae from 24 datasets within the UNITY framework [29]. DESI DR2 further tightened baryon acoustic oscillation constraints and strengthened the motivation to test evolving dark energy models [30]. The resulting HDE literature is therefore not simply more precise than the pre 2021 literature. It is more exposed to cross dataset inconsistency because independent distance ladders and early universe calibrations now overlap tightly in parameter space.

6.2 The parameter c and the late versus early universe split

The clearest numerical result of the recent literature is the instability of the preferred c value under dataset changes. In the DESI DR1 analysis by Li and collaborators, DESI alone gave $c = 0.890$ with an upper uncertainty of 0.130 and a lower uncertainty of 0.250 [23]. CMB information alone preferred $c = 0.452$ with a much smaller upper uncertainty. Combining CMB with DESI gave $c = 0.462$ with uncertainties of order a few hundredths. In sharp contrast, DESI combined with PantheonPlus gave $c = 1.001$, with Union3 gave $c = 1.150$, and with DESY5 gave $c = 1.106$. These late time combinations cluster near or above the de Sitter boundary. Adding CMB moved the same three supernova combinations to $c = 0.673$, 0.642, and 0.701. The shift is too large to be summarized as a simple tightening of one posterior. It is a change in the preferred physical regime.

The newest DESI DR2 late time analysis reinforces this interpretation. Huang, Liu, and Shao combined cosmic chronometers, supernovae, DESI DR2 baryon acoustic oscillations, and growth information and obtained $c = 1.011$ with an upper uncertainty of 0.076 and a lower uncertainty of 0.072 when redshift space distortion information was included [31]. The same fit gave $H_0 = 67.860$ with an upper uncertainty of 1.534 and a lower uncertainty of 1.579 $\text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_{m0} = 0.270$ with uncertainties near 0.009, $r_d = 146.957$ with uncertainties near 3.3 Mpc, and $\sigma_8 = 0.875$ with uncertainties near 0.038. Late time DESI DR2 information therefore remains entirely compatible with c near unity. It does not reproduce the much smaller c values obtained when CMB information dominates.

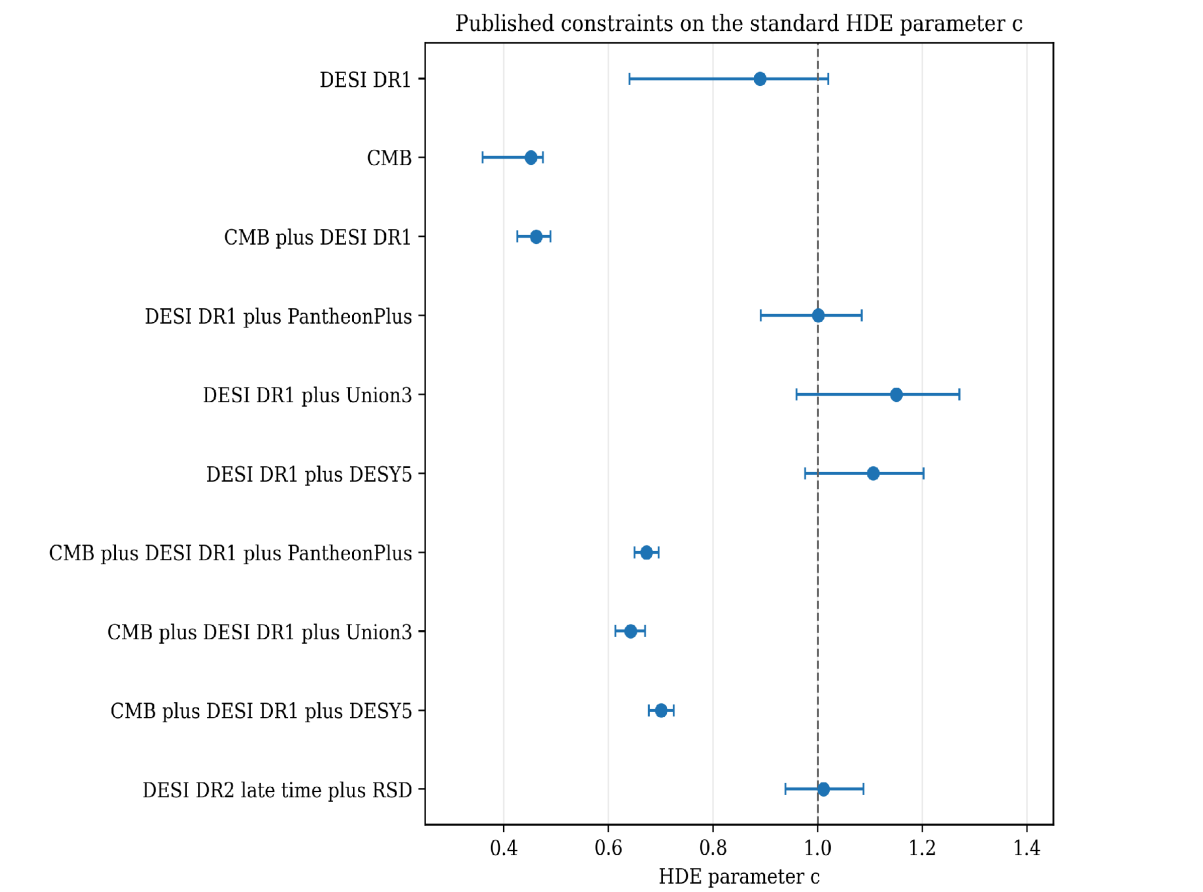


Figure 3. Original compilation of published one parameter constraints on c . The DESI DR1 values are from Li et al. [23]. The DESI DR2 late time value including growth information is from Huang et al. [31]. The vertical line marks c equal to one. The figure demonstrates the shift between CMB driven phantom solutions and late time solutions near or above unity.

Table 3. Representative constraints on the standard HDE parameter c . Asymmetric uncertainties are quoted at the confidence level reported by the source.

Dataset combination	C	Lower error	Upper error	Physical reading
DESI DR1 [23]	0.890	0.250	0.130	Broadly compatible with unity
CMB [23]	0.452	0.093	0.023	Deep phantom tendency

Dataset combination	C	Lower error	Upper error	Physical reading
CMB plus DESI DR1 [23]	0.462	0.036	0.027	Deep phantom tendency
DESI DR1 plus PantheonPlus [23]	1.001	0.110	0.083	Near de Sitter boundary
DESI DR1 plus Union3 [23]	1.150	0.190	0.121	Quintessence tendency
DESI DR1 plus DESY5 [23]	1.106	0.130	0.096	Quintessence tendency
CMB plus DESI DR1 plus PantheonPlus [23]	0.673	0.023	0.023	Phantom
CMB plus DESI DR1 plus Union3 [23]	0.642	0.028	0.028	Phantom
CMB plus DESI DR1 plus DESY5 [23]	0.701	0.024	0.024	Phantom
DESI DR2 late time plus RSD [31]	1.011	0.072	0.076	Near de Sitter boundary

6.3 Bayesian evidence and the danger of likelihood only conclusions

The same DESI DR1 study reported a striking difference between late time and CMB inclusive evidence. Relative to Λ CDM, the log Bayes factors for standard HDE were negative for every quoted dataset combination. Their magnitudes were modest for late time data, with values 2.203, 1.395, and 0.189 for PantheonPlus, Union3, and DESY5 combinations with DESI. Once CMB was added, the magnitudes increased dramatically to 28.616, 26.878, and

29.498. Interacting HDE reduced these large penalties to 24.780, 23.226, and 24.097, but did not reverse the evidence ordering [23]. The message is not that HDE cannot fit the data. It can. The message is that the additional freedom and the location of the posterior are not rewarded by the integrated evidence when the full dataset is used.

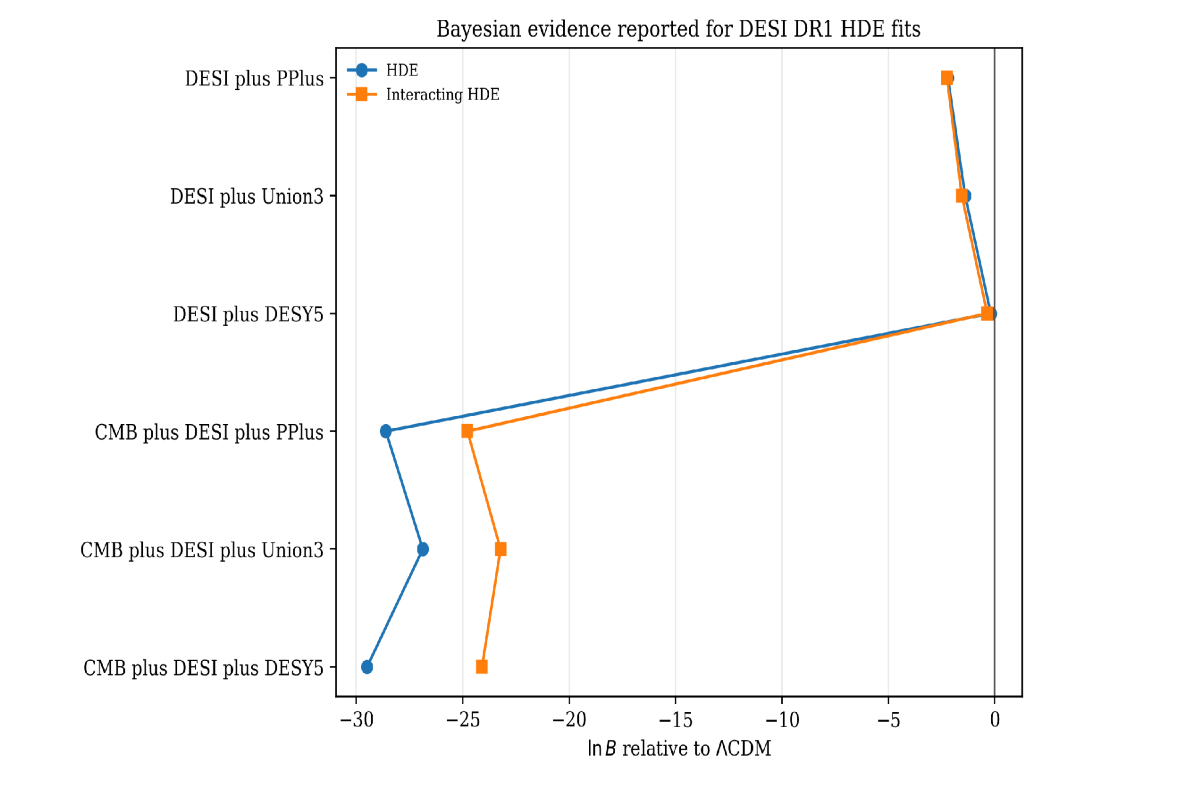


Figure 4. Original representation of the log Bayes factors reported by Li et al. [23]. Negative values favor Λ CDM under the convention used here. Late time evidence penalties are modest for some supernova combinations, while CMB inclusive combinations are strongly unfavorable to both HDE and interacting HDE.

Table 4. Log Bayes factors relative to Λ CDM from the DESI DR1 analysis. Negative values indicate evidence favoring Λ CDM.

Dataset	HDE ln B	Interacting HDE ln B
DESI plus PantheonPlus	−2.203	−2.248
DESI plus Union3	−1.395	−1.553
DESI plus DESY5	−0.189	−0.357

Dataset	HDE ln B	Interacting HDE ln B
CMB plus DESI plus PantheonPlus	-28.616	-24.780
CMB plus DESI plus Union3	-26.878	-23.226
CMB plus DESI plus DESY5	-29.498	-24.097

6.4 The Hubble tension

Claims that holographic dark energy resolves the Hubble tension must be specified by model family and dataset. Yarahmadi and Salehi found a reduced tension in a Barrow plus Granda Oliveros construction with neutrino freedom [16]. However, broader comparisons do not support a generic HDE solution. Plaza, León, and Kraiselburd found that a holographic model in unimodular gravity did not produce a statistically preferred resolution when confronted with DESI DR2 [32]. Luciano, Paliathanasis, and Saridakis concluded that Barrow and Tsallis models constrained with DESI DR2 remain unable to alleviate the H_0 tension and are not favored over Λ CDM by information criteria [33].

The systematic six model comparison by Li and Wang is especially informative because it holds the observational strategy approximately fixed while changing the HDE class [34]. With DESI, CMB, and DESY5, models built from the Hubble scale or Hubble scale combinations retained large H_0 discrepancies. The reported tensions were 5.32 standard deviations for the selected Tsallis Hubble scale model, 5.84 for generalized Ricci dark energy, and 6.31 for one interacting Hubble cutoff model. Future event horizon families performed better but did not eliminate the problem. The corresponding values were 2.49 for ordinary HDE, 3.12 for the Barrow event horizon model, and 4.49 for the selected interacting event horizon model. The cutoff therefore matters, but no universal resolution follows from holography itself.

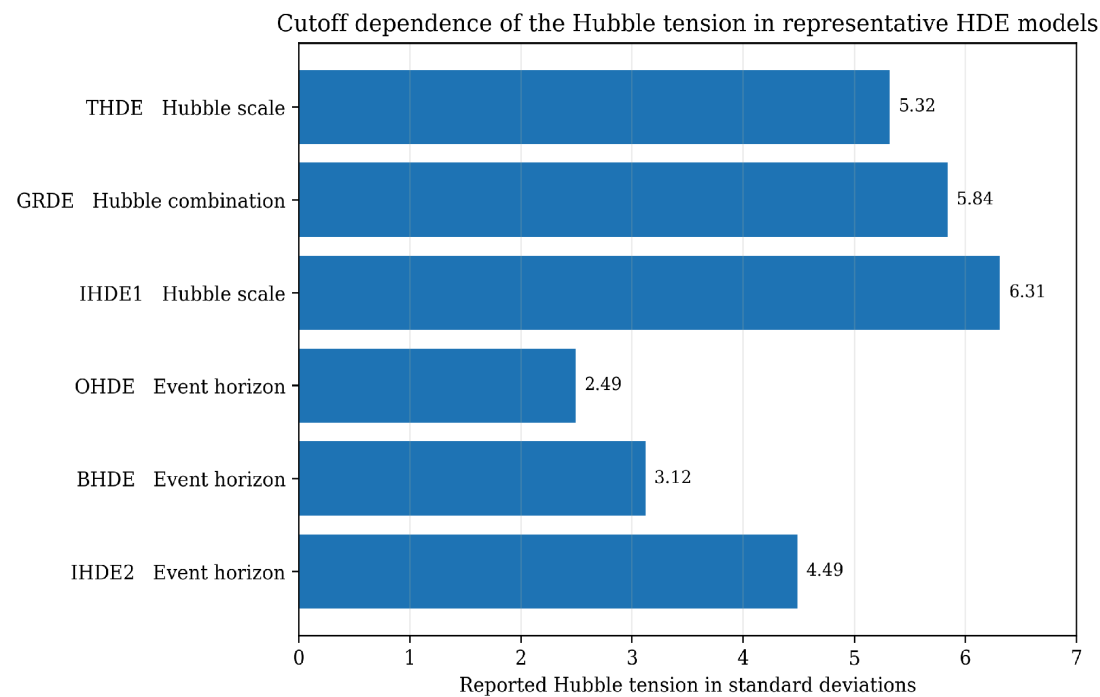


Figure 5. Original summary of the Hubble tension values reported for six representative models by Li and Wang [34] using a DESI, CMB, and DESY5 combination. The comparison shows that future event horizon models can reduce the discrepancy relative to Hubble scale constructions, but the effect is model dependent and does not constitute a complete resolution.

Table 5. Reported Hubble tension for representative HDE families using the DESI, CMB, and DESY5 combination in Ref. [34].

Representative model	Cutoff family	H0 tension in standard deviations
THDE	Hubble scale	5.32
GRDE	Hubble combination	5.84
IHDE1	Hubble scale	6.31
OHDE	Future event horizon	2.49
BHDE	Future event horizon	3.12

Representative model	Cutoff family	H_0 tension in standard deviations
IHDE2	Future event horizon	4.49

7 Perturbations, structure formation, and theoretical consistency

The perturbation sector is the point at which many apparently successful dark energy backgrounds become physically distinguishable. Holographic models are especially sensitive because the energy density can depend on a horizon quantity rather than a local fluid variable. Two issues must be separated. The first is formal closure of perturbation equations. The second is empirical agreement with growth, lensing, matter power spectra, and cosmic microwave background anisotropies.

The effective field theory analysis already shows that a phantom background can coincide with loss of control in the scalar sector [7]. Astashenok and Tepliakov reached a complementary conclusion from the generalized entropy side, arguing that standard fluid perturbation intuition can be misleading for a dark component whose origin is tied to a cosmological boundary [17]. Landim demonstrated the empirical consequence in a Hubble scale interacting model, where the predicted power spectra failed despite a plausible background [12]. Together these studies imply a strict standard for future work. Any observational claim based on background distances should identify the perturbation prescription and its regime of validity.

Recent Tsallis work makes the cutoff dependence particularly explicit. Das compared particle horizon and future event horizon prescriptions using growth factor, growth rate, and redshift space distortion information [35]. The future event horizon version could remain compatible with growth observations and, for suitable Tsallis parameter values, give a fit comparable to the standard model. The particle horizon version generally failed to reproduce the observed growth history. This is one of the clearest demonstrations in the recent literature that structure formation can discriminate between infrared prescriptions that appear less distinct at background level.

Growth information also changes how one should read the 2026 late time standard HDE result. Huang and collaborators included redshift space distortion as a consistency test and found σ_8 near 0.875 in their combined fit [31]. They correctly emphasized that this does not constitute a complete perturbative stability analysis. A full test would require a consistent perturbation implementation across all relevant scales, including the dark energy sector, rather than a growth observable appended to a background likelihood. This distinction should become standard practice in HDE phenomenology.

8 Modified gravity, geometry, and data driven generalizations

Holographic dark energy has increasingly been embedded in nonstandard gravitational backgrounds. Brans Dicke constructions allow the effective Planck scale to evolve [14]. Unimodular gravity provides a different route to the vacuum sector [32]. Nonflat HDE and

IHDE models introduce curvature as an additional geometric degree of freedom [25]. These extensions can reveal theoretical correspondences, but they also enlarge the parameter space in which cosmological tensions can be redistributed. For this reason, an improved maximum likelihood in an extended framework is less informative than a combined assessment of posterior consistency, information criteria, and evidence.

A particularly interesting shift is the move from named parametric deformations to data driven reconstruction. Zapata, Garcia Arroyo, Adil, and Vazquez generalized the relation between holographic density and the future horizon using a spline with nodal freedom [36]. They found that standard HDE was strongly disfavoured relative to a three node reconstruction, while the flexible reconstructed model improved the fit relative to Λ CDM by a substantial change in chi squared. This result is scientifically valuable because it asks a different question. Instead of testing one microscopic deformation, it asks what functional departure from standard HDE is preferred by current distances and H_0 information. The interpretation must nevertheless distinguish improvement in chi squared from Bayesian evidence after accounting for the enlarged function space.

The reconstruction perspective may become a bridge between phenomenology and theory. If independent datasets repeatedly prefer the same redshift dependence, that shape can be used to infer what class of cutoff or entropy correction could generate it. If the preferred shape changes when the supernova compilation or early universe prior changes, the reconstruction is instead diagnosing dataset inconsistency. HDE is unusually well suited to this approach because the horizon relation itself is a compact place to encode departures from the standard model.

9 Critical synthesis of the 2021 to 2026 literature

9.1 What has become more convincing

First, holographic dark energy now has a more serious theoretical language than it did five years ago. The effective field theory program clarifies how a nonlocal looking background can emerge from a local covariant framework and identifies the scalar mode that controls the ultraviolet and infrared connection [6, 7]. Second, modern analyses increasingly use several independent distance datasets rather than a single background probe. Third, growth and perturbation studies have begun to eliminate model variants that would survive a purely geometric analysis [12, 17, 35]. Fourth, generalized entropy models are now being tested with Bayesian evidence rather than only with best fit curves [19]. These are substantive advances.

9.2 What remains unresolved

The most serious unresolved issue is internal dataset dependence in the standard HDE parameter c . The difference between c near one from late time DESI and supernova information and c near 0.65 to 0.70 after including CMB is not a small calibration detail [23, 31, 37]. Naik independently found the same qualitative split with DESI DR2, reporting supernova dominated combinations that favor c above about 1.2 and CMB inclusive combinations near $c = 0.69$ [37]. A one parameter physical model cannot simultaneously interpret these values as a unique property of the dark energy sector without explaining why the preferred regime changes so strongly with the data combination.

The second unresolved issue is the physical meaning of entropy deformation constraints. A Barrow parameter near zero in a Granda Oliveros model and a value above about 0.86 in a

generalized event horizon framework are both legitimate outputs of their respective likelihoods [16, 19]. They do not measure the same effective theory. Review articles and original papers should therefore avoid statements such as observations constrain the Barrow parameter without naming the exact energy density prescription, cutoff, gravity theory, and dataset. The same caution applies to Tsallis and Kaniadakis parameters.

The third issue is that the Hubble tension has become an overly broad benchmark. A model can shift H_0 upward by increasing freedom, yet still lose evidence and create growth or early universe tension. The six model comparison shows that future event horizon models generally perform better on H_0 than Hubble scale variants, but none of the tested cases gives a universal solution [34]. Recent DESI DR2 HDE work likewise concludes that standard HDE does not significantly resolve the tension [31, 37]. A credible resolution would require simultaneous agreement with CMB calibration, baryon acoustic oscillations, supernova distances, growth, and a statistically competitive model evidence.

9.3 A practical hierarchy for model assessment

The recent literature suggests a useful hierarchy. The first level is background viability, including a matter era and late acceleration. The second is perturbative closure and absence of ghost or gradient pathologies in the regime used for inference. The third is agreement with both geometry and growth. The fourth is cross dataset parameter consistency. The fifth is model evidence relative to Λ CDM and to other HDE prescriptions. Models that stop at the first level are now preliminary constructions rather than observationally mature cosmologies. Models that reach the third level but exhibit severe early versus late parameter shifts remain diagnostically interesting but not established alternatives. Only models that survive all five levels can plausibly compete as a precision cosmology.

10 Research priorities for the next generation of holographic dark energy studies

1. Future analyses should implement perturbations at the same theoretical level as the background. The perturbation variables, sound speed assumptions, interaction perturbations, and stability domain should be stated explicitly before fitting growth or cosmic microwave background information.
2. Infrared cutoff choice should be treated as a model selection problem. Future event horizon, Hubble, Ricci, Granda Oliveros, and particle horizon prescriptions should be compared with the same data, priors, and evidence calculation whenever possible.
3. Generalized entropy constraints should be reported together with their exact map from entropy to energy density. A deformation parameter has no universal observational meaning across inequivalent constructions.
4. DESI DR2 and later data should be analyzed with several supernova compilations in parallel. The difference between PantheonPlus, Union3, and DES five year posteriors is itself information about systematic sensitivity rather than a nuisance to be hidden in a combined number.
5. Early universe information should be introduced in stages. Reporting late time only, CMB only, and joint posteriors makes internal tension visible. A joint best fit alone can conceal mutually displaced likelihoods.

6. Bayesian evidence or an equally principled complexity penalty should accompany AIC and chi squared comparisons. A small improvement in fit is not sufficient when an entropy deformation, interaction, curvature, or functional reconstruction adds substantial parameter volume.

7. Reconstruction methods should be used as diagnostics for theory building. Stable reconstructed features that repeat across datasets can guide the design of new holographic cutoffs. Features that disappear under dataset substitution are more likely to identify observational inconsistency.

8. Forecasts for Euclid, Rubin Observatory, Roman, future DESI releases, CMB S4, and next generation standard sirens should target the observables that distinguish HDE families, especially growth, lensing, the redshift dependence of the equation of state, and correlated constraints on c and H_0 .

11 Conclusions

The five years from 2021 to 2026 have moved holographic dark energy from broad background phenomenology toward a more demanding phase of precision testing. The field now contains covariant effective descriptions, detailed perturbation studies, generalized entropy constructions, interaction models, nonflat extensions, modified gravity embeddings, and flexible data driven reconstructions. This diversity is intellectually productive, but it also makes the generic label HDE scientifically insufficient. The infrared cutoff and entropy prescription define different cosmologies and must be judged separately.

The standard future event horizon model remains the cleanest benchmark because its main phenomenology is controlled by a single parameter c . That simplicity exposes its current tension. Late time DESI and supernova combinations can place c close to or above one, while CMB inclusive analyses repeatedly favor c well below one. The resulting phantom regime also interacts with theoretical stability questions identified by effective field theory. Interacting HDE can shift the posterior and soften some evidence penalties, but present analyses do not establish it as statistically superior to Λ CDM. Generalized entropy models provide valuable microscopic ideas, yet the observationally inferred deformation can range from nearly zero to order unity depending on the construction. Those values cannot be compared without specifying the cutoff and entropy to density map.

The most robust empirical conclusion is therefore not that holographic dark energy has been ruled out, nor that it has solved the major tensions of cosmology. It is that current data sharply discriminate among holographic implementations. Future event horizon prescriptions tend to perform better than Hubble scale alternatives in several recent comparisons, growth measurements can exclude cutoff choices that look viable in background expansion, and Bayesian evidence often remains less favorable than likelihood based summaries suggest. The field will progress most rapidly by replacing ever larger catalogs of background models with perturbation complete, statistically disciplined, cross dataset consistent theories. In that form holographic dark energy remains a powerful laboratory for testing whether quantum gravitational ideas can leave measurable signatures in cosmic acceleration.

Author generated figure and data note

All five figures in this review were generated specifically for this manuscript from analytical equations or numerical values reported in the cited literature. No journal artwork or subscription figure has been reproduced. Numerical tables transcribe published parameter constraints or summarize model definitions. Readers should consult the original papers for likelihood choices, priors, covariance treatment, and full posterior information.

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