

Holographic dark energy

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Abstract. The holographic principle provides a fundamental relation between the ultraviolet (UV) and infrared (IR) cutoffs of a quantum field theory. Holographic Dark Energy (HDE) arises from the application of this principle to cosmology, offering a dynamical explanation for the current accelerated expansion of the Universe. In this review, we summarize the theoretical foundations of HDE, the implications of various IR cutoffs including the Hubble horizon, particle horizon, and future event horizon, and their corresponding thermodynamic behaviors. We present the equation of state and the deceleration parameter for the standard HDE model. Finally, we review observational constraints on the HDE parameter c using Cosmic Microwave Background (CMB) measurements from Planck, Baryon Acoustic Oscillations (BAO), and Type Ia Supernovae (SNIa), showing that a phantom regime ($c < 1$) is generally favored by current data.

Keywords: Dark Energy; Holographic Principle; Cosmology; Observational Constraints.

1 Introduction

The discovery of the late-time acceleration of the Universe remains one of the most significant challenges in modern cosmology. Among the plethora of theoretical models proposed to explain this phenomenon, Holographic Dark Energy (HDE) stands out as an approach deeply rooted in quantum gravity. The core idea stems from the holographic principle, which suggests that the number of degrees of freedom in a bounded system should scale with its boundary area rather than its volume.

Applying the Bekenstein-Hawking entropy bound to cosmological scales, Cohen et al. proposed that the total energy in a region of size L should not exceed the mass of a black hole of the same size. This imposes a relationship between the ultraviolet (UV) cutoff Λ_{UV} and the infrared (IR) cutoff L :

$$L^3 \rho_\Lambda \leq L M_p^2, \quad (1)$$

where ρ_Λ is the zero-point energy density associated with the UV cutoff and $M_p = 1/\sqrt{8\pi G}$ is the reduced Planck mass. Saturating this inequality yields the energy density of the holographic dark energy:

$$\rho_D = 3c^2 M_p^2 L^{-2}, \quad (2)$$

where c is a dimensionless numerical constant.

2 The Choice of Infrared Cutoff

The phenomenological success of the HDE model strongly depends on the choice of the IR cutoff L . Several cosmological lengths have been proposed:

2.1 Hubble Horizon

If we choose the Hubble scale $L = H^{-1}$, the energy density becomes $\rho_D = 3c^2 M_p^2 H^2$. This yields an equation of state (EoS) $w_D = 0$, which behaves as pressureless dust and cannot drive cosmic acceleration.

2.2 Particle Horizon

Using the particle horizon $L = a \int_0^t \frac{dt'}{a(t')}$ yields an EoS parameter $w_D > -1/3$. This is also insufficient to explain the current accelerated expansion without violating the strong energy condition.

2.3 Future Event Horizon

The most successful candidate is the future event horizon, defined as:

$$R_h = a \int_t^\infty \frac{dt'}{a(t')} = a \int_a^\infty \frac{da'}{H a'^2}. \quad (3)$$

Proposed by Li, this choice correctly produces an accelerating universe. Using $L = R_h$ in Eq. (2), the fractional energy density of dark energy is defined as $\Omega_D = \rho_D / (3M_p^2 H^2) = c^2 / (H^2 R_h^2)$.

3 Equation of State and Cosmic Evolution

Taking the derivative of the future event horizon with respect to cosmic time t , we obtain:

$$\dot{R}_h = H R_h - 1 = \frac{c}{\sqrt{\Omega_D}} - 1. \quad (4)$$

By substituting this into the energy conservation equation $\dot{\rho}_D + 3H(1+w_D)\rho_D = 0$, the equation of state parameter for HDE takes the exact analytical form:

$$w_D = -\frac{1}{3} - \frac{2}{3} \frac{\sqrt{\Omega_D}}{c}. \quad (5)$$

This is a dynamical EoS. If $c = 1$, the model asymptotically approaches a de Sitter phase ($w_D \rightarrow -1$). Interestingly, for $c < 1$, the EoS crosses the phantom divide ($w_D < -1$) at late times, potentially leading to a Big Rip singularity. For $c > 1$, the model remains in the quintessence regime ($w_D > -1$).

The deceleration parameter $q = -\ddot{a}/(aH^2)$ can be expressed directly in terms of Ω_D and c :

$$q = \frac{1}{2} - \frac{\Omega_D}{2} + \Omega_D \left(\frac{1}{2} - \frac{\sqrt{\Omega_D}}{c} \right). \quad (6)$$

4 Observational Constraints

The free parameter c governs the entire evolutionary history of the dark energy. Extensive observational studies have been conducted to constrain c using data from the Cosmic Microwave Background (CMB), Baryon Acoustic Oscillations (BAO), and Type Ia Supernovae (SNIa).

As summarized in Table 1, combinations of Planck temperature data with BAO and SNIa strongly favor $c < 1$. This implies that the standard HDE model with a future event horizon prefers a phantom-like behavior at the current epoch.

Dataset Combination	Constraint on c
Planck CMB + WP + Lensing	0.508 ± 0.207
Planck CMB + WP + BAO + HST	0.484 ± 0.070
Planck CMB + WP + BAO + SNIa	0.495 ± 0.039
WMAP9 + BAO + SNIa	0.642 ± 0.066

Table 1: Observational constraints on the HDE parameter c at 1σ confidence level from cosmological datasets.

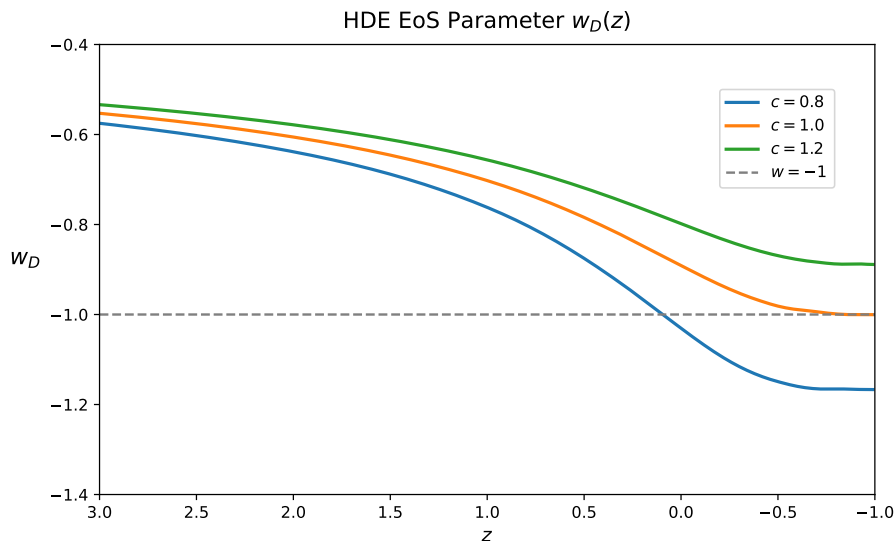


Figure 1: Evolution of the Holographic Dark Energy equation of state parameter w_D as a function of redshift z for interaction parameters $c = 0.8, 1.0, 1.2$. For $c < 1$, the trajectory crosses the phantom divide ($w = -1$) at late times.

5 Conclusions

The Holographic Dark Energy model provides an elegant, physically motivated framework for explaining cosmic acceleration by bridging UV and IR energy scales. By adopting the future event horizon as the IR cutoff, the model successfully avoids the no-go theorems associated with the Hubble and particle horizons. Current observational data consistently favor a parameter value $c < 1$, pointing toward a phantom-like evolution of the late universe. Future surveys, such as DESI, will be highly instrumental in placing tighter bounds on c and testing interacting variants of the HDE model.

References

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