Constraining Holographic Dark Energy Models with Current Cosmological Observations

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ABSTRACT

The accelerating expansion of the universe remains one of the most profound discoveries in modern cosmology, motivating a wide class of dark energy models to explain it. Among these, the holographic dark energy (HDE) model, which is based on the holographic principle of quantum gravity, offers a fascinating framework for explaining cosmic acceleration in the late time. In this paper, we jointly analyze recent cosmological datasets, such as gamma-ray burst(GRB) distance indicators, cosmic chronometer (CC)measurements of the Hubble parameter, and Type Ia supernovae from the Pantheon sample, to present observational constraints on HDE models. We constrain the HDE parameters using Markov Chain Monte Carlo methods and a Bayesian statistical framework. Our findings show that late-time cosmic acceleration can still be explained by HDE models. These findings highlight how crucial holographic methods are for examining the nature of cosmic acceleration and dark energy.

INTRODUCTION

Holographic Dark Energy (HDE)

- **Inspired by the holographic principle:** information in a volume is encoded on its boundary.
- Dark energy density tied to the cosmic horizon scale, offering a dynamic explanation for cosmic acceleration without a constant term.
- **Energy density formula:**

$$\rho_{DE} = 3c^2 M_p^2 L^{-2},$$

  where c is a dimensionless parameter, L horizon length, M_p Planck mass.
- **Models:** Ricci DE, New Agegraphic DE (NADE),Barrow Holographic DE (BHDE).
- **Datasets:** SNe Ia, Cosmic Chronometers (CC), Gamma-Ray Bursts (GRBs).

METHODOLOGY

Bayesian Parameter Estimation & Model Comparison

- Bayesian statistics estimate cosmological parameters using **Markov Chain Monte Carlo (MCMC)** simulations, which efficiently sample the posterior distribution of model parameters given the data.
- The likelihood function combines contributions from all datasets:

$$L_{tot} \propto \exp(-\tfrac{1}{2}\chi^2_{tot}), \text{ where } \chi^2_{tot} = \chi^2_{SN} + \chi^2_{CC} + \chi^2_{GRB}$$

Model Selection Criteria

- **Akaike Information Criterion (AIC):**

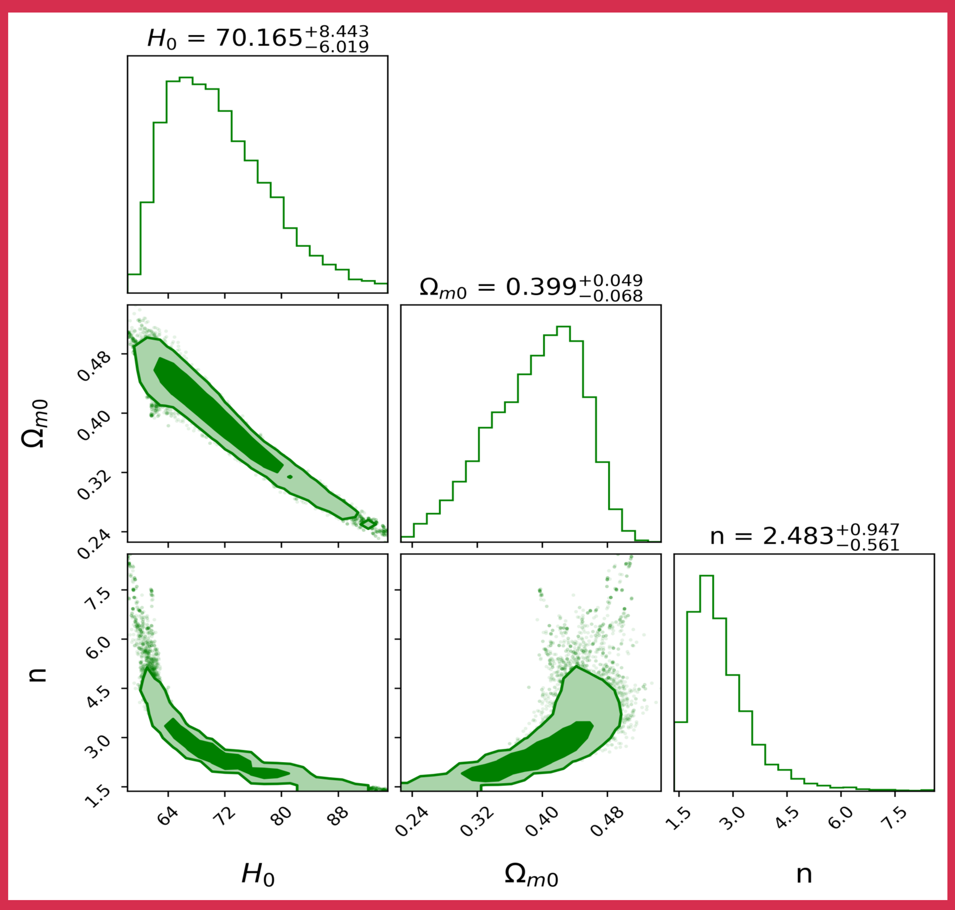
$$\mathrm{AIC} = \chi^2_{min} + 2k$$

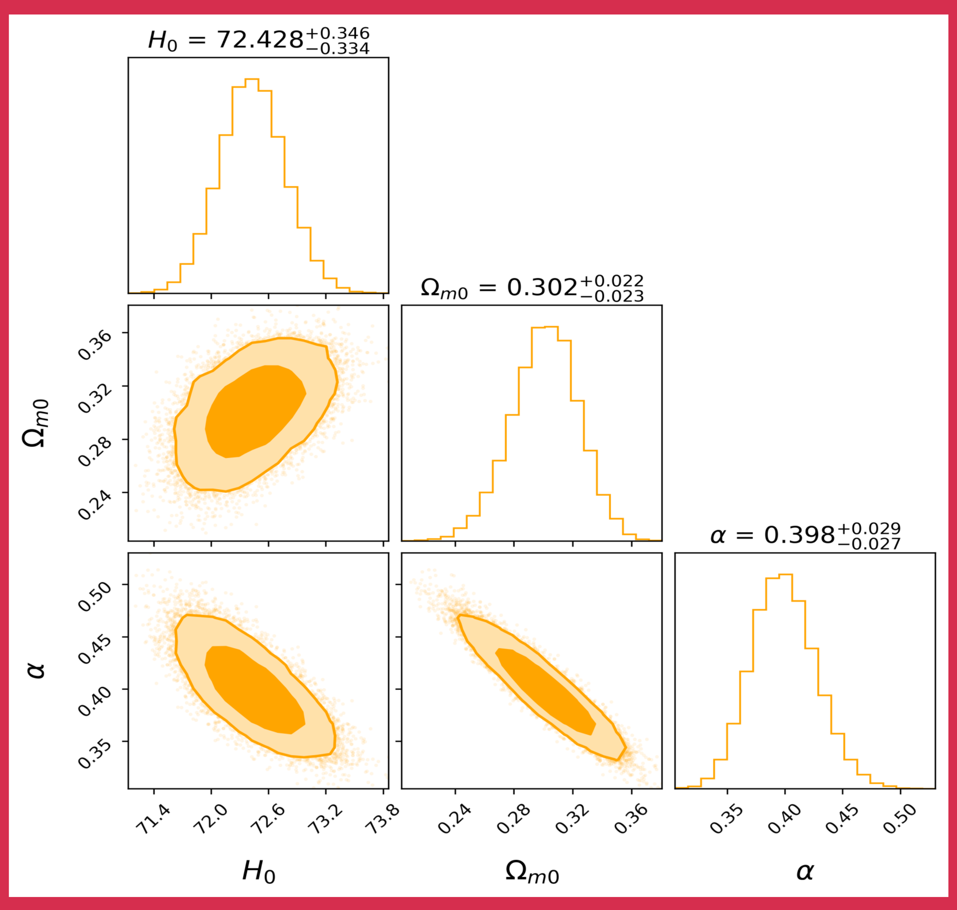
  where k: number of free parameters.
- **Bayesian Information Criterion (BIC):**

$$BIC = \chi^2_{min} + k \ln N$$

  where N: total number of data points.

Results:Posterior distribution of holographic dark energy models





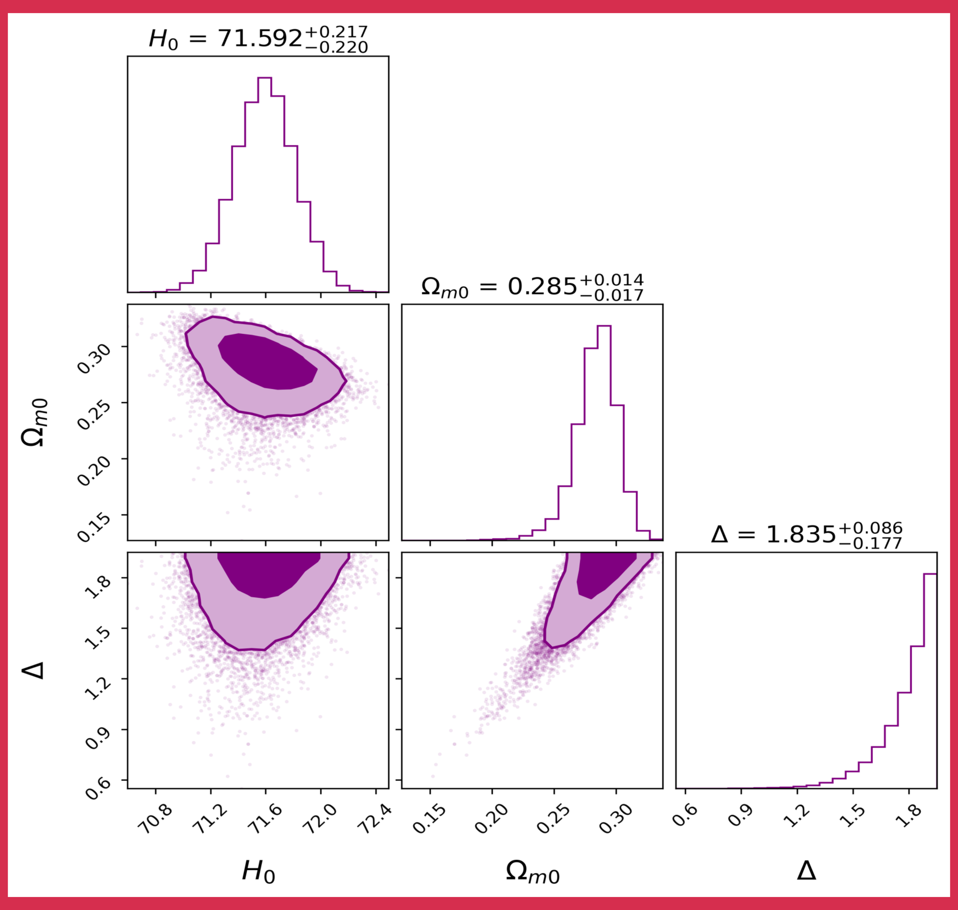
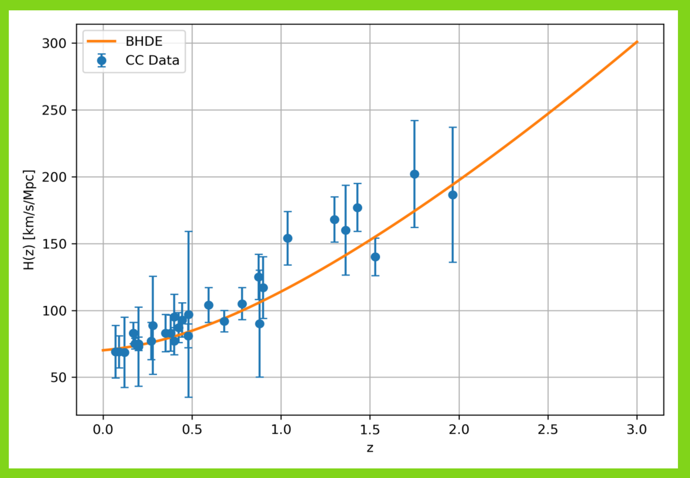
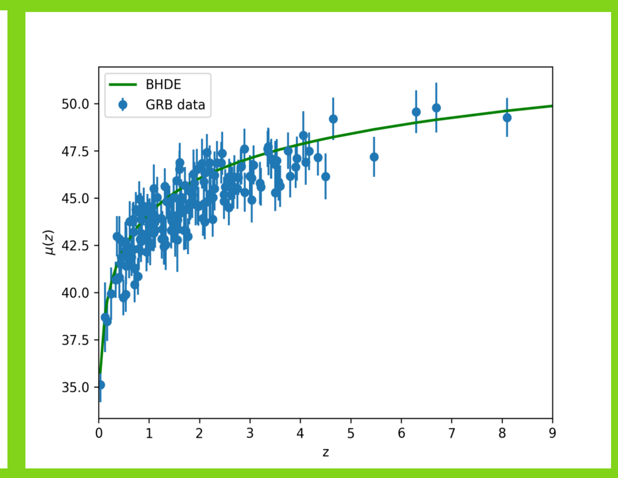
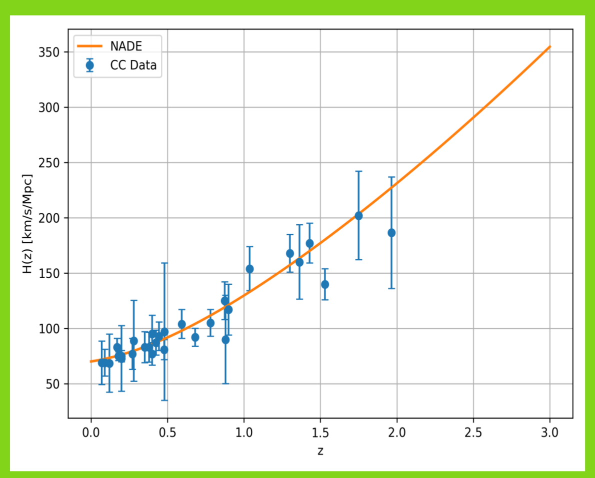
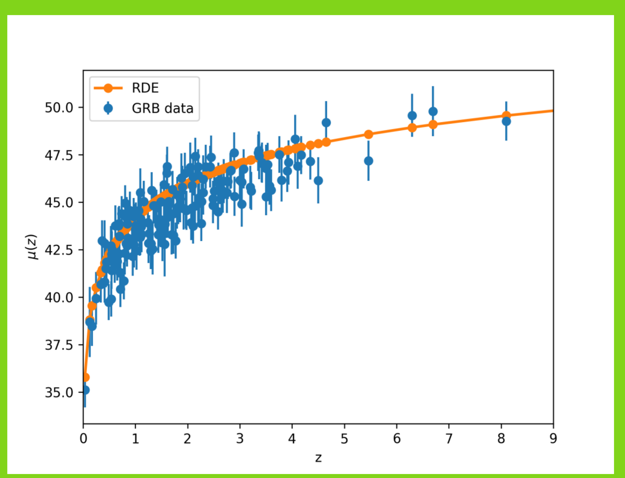


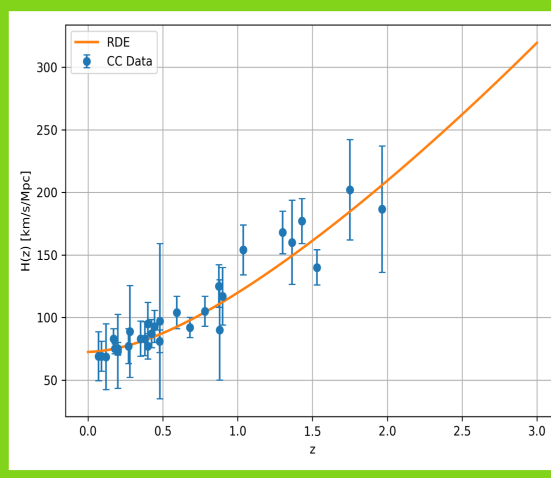
Fig.1,2, 3: Corner plot for the NADE,BHDE and RDE models parameters constrained with CC + GRB + SN data. The diagonal plots show the marginalized one-dimensional distributions, while the off-diagonal plots show the joint 68% and 95% confidence regions for the NADE,RDE and BHDE models, respectively.











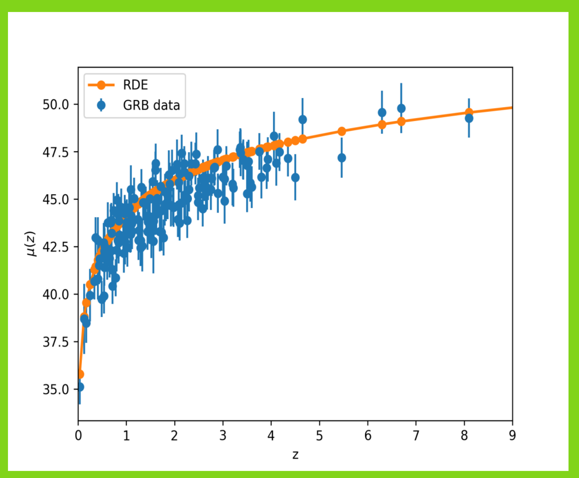


Fig.1, 3, 5: The corresponding redshift z and expansion rate H(z) evolution for BHDE,NADE and RDE are also shown, respectively. Fig.2,4,6 : The Comparison of the distance modulus μ(z) for the BHDE, NADE,RDE models with GRB observations. Blue points with error bars denote the GRB data, while the curve represents the theoretical BHDE,NADE and RDE prediction.

Table 1: Best-fit values of the cosmological parameters H_0 , Ω_{m0} and the additional model-specific parameter for BHDE, RDE, and NADE models respectively.

Model	H_0 [km s⁻¹ Mpc⁻¹]	Ω_{m0}	Additional Parameter
BHDE	$71.59^{+0.22}_{-0.22}$	$0.285^{+0.014}_{-0.017}$	$\Delta = 1.834^{+0.086}_{-0.177}$
RDE	$72.428^{+0.334}_{-0.346}$	$0.302^{+0.022}_{-0.023}$	$\alpha = 0.398^{+0.029}_{-0.027}$
NADE	$70.165^{+8.443}_{-6.019}$	$0.399^{+0.049}_{-0.068}$	$n = 2.483^{+0.947}_{--0.561}$

Table 2: Model comparison using χ^2, AIC, and BIC values for NADE, RDE, and BHDE.

Model	χ^2min	AIC	BIC
NADE	600.7017	604.7017	614.6110
RDE	600.7235	604.7235	614.6328
BHDE	612.3464	618.3464	633.2103

Summary

➢We have find that the BHDE and RDE not only achieve strong agreement with observational evidence but also impose tighter bounds than the NADE approach .
➢BHDE and RDE best-fit estimates fall between Planck and SHOES measurements, leaning toward the SH0ES result.
➢ BHDE and RDE models could represent a more plausible description of late-time acceleration while also contributing meaningfully to the debate on the Hubble tension.
➢Since NADE and RDE cannot be clearly distinguished with present data we have used, future probes such as redshift drift tests, SKA, or ELT observations,including structure growth measurements ,will be needed to break this degeneracy and clarify their predictions for cosmic evolution.

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