Constraining the emergent dark energy models with cosmology-independent observational data

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Abstract

In this work, we investigate the phenomenologically emergent dark energy (PEDE) model and its generalized form, namely the generalized emergent dark energy (GEDE) model, which introduces a free parameter Δ that can discriminate between the ΛCDM model and the PEDE model. Fitting the emergent dark energy (EDE) models with the observational datasets including the cosmology-independent gamma-ray bursts (GRBs) at high-redshift and the observational Hubble data (OHD), we find a large value of H_0 which is close to the results of local measurement of H_0 from the SH0ES Collaboration in both EDE models. These results suggest that PEDE and GEDE models can be possible alternative to the standard cosmological model, pending further theoretical explorations and observational verifications.

Keywords: Hubble constant, Dark energy, Cosmological parameters, GRBs

1 Introduction

One of the crucial cosmological discoveries was the late-time accelerated expansion of the universe [1, 2], a phenomenon that remains mysterious within the current cosmological framework. To provide a plausible explanation, the concept of an exotic cosmic component dark energy (DE) which produces negative pressure with a negative equation of state was introduced. The late-time accelerated expansion of the universe can be modeled by the ΛCDM model,which combining the simplest assumption for dark energy: the cosmological constant Λ with an equation of state (EoS) parameter $w = -1$ and the cold dark matter (CDM) component. The standard ΛCDM model has successfully described numerous cosmological observations, including Type Ia supernovae (SNe Ia) [3, 4], baryon acoustic oscillations (BAO) [5–8], and the cosmic microwave background (CMB) [9–12]. The measurement of the Hubble constant (H_0) has revealed the current accelerated expansion of the Universe [13]. The H_0 tension is one of the major issues in modern cosmology in which the measurements discrepancy between the local measurement of H_0 by the *Supernova H0 for the Equation of State* (SH0ES) collaboration [14–18] and the early Universe using Planck CMB observations assuming the ΛCDM model [11, 12] can reach at 5.3σ. At a 1-σ confidence level, SH0ES measurement of the distance ladder calibrated by Cepheids yields $H_0 = 73.01 \pm 0.99\,\mathrm{km\,s^{-1}Mpc^{-1}}$ [18]; whereas the Planck collaboration which uses temperature and polarization anisotropies in the CMB obtain $H_0 = 67.27 \pm 0.6\,\mathrm{km\,s^{-1}Mpc^{-1}}$ [12]. The H_0 tension implies that either there are considerable but not accounted for systematic errors in CMB observations, or modifications to the standard ΛCDM model might be considered.

With a motivation of alleviating the H_0 tension, Li and Shafieloo [19] proposed a new dark energy model called the Phenomenologically Emergent Dark Energy (PEDE) model as a potential alternate to the ΛCDM model. The model effectively replaces the cosmological constant with a hyperbolic tangent function of redshift which causes the DE to emerge as a function of the cosmic time at later times. Pan et al. [20] found that the tension on H_0 is clearly alleviated for the PEDE model in a six parameter space similar to the spatially flat ΛCDM model with the combined datasets. Koo et al. [21] used a nonparametric iterative smoothing method on the Joint Light-curve Analysis (JLA) SNe Ia data to show that the PEDE model are consistent with those of the standard model. Yang et al. [22] considered the effects of adding curvature in the PEDE model with the Planck 2018 CMB temperature and polarization data, BAO and Pantheon sample [4] which contains 1048 SNe Ia data. Liu et al. [23] used a newly compiled sample the ultra-compact structure in radio quasars and strong gravitational lensing systems with quasars to constrain the spatially flat and non-flat PEDE model.

Later on, Li and Shafieloo [24] proposed the Generalized Emergent Dark Energy (GEDE) model with extra parameters to describe the properties of dark energy evolution: the free parameter Δ describe the evolution slope of dark energy density, and the transition redshift z_t which identifies where dark energy density equals matter density is not a free parameter. The GEDE model has the flexibility to include both the ΛCDM model and the PEDE model as two of its special limits. Motta et al. [25] briefly summarize the characteristics of a list of dark energy models including the PEDE and GEDE models with the joint cosmological samples.

There is an interesting idea for the H_0 tension for H_0 with a redshift evolving of observational data. Recently, Dainotti et al. [26] find a slowly decreasing trend of H_0 value with a function mimicking the redshift evolution. The local distance ladder of SN Ia calibrated by Cepheids can reach at $z < 0.01$, while the CMB data is near $z \sim 1000$. Therefore, cosmological data in the mid-redshift region between the local distance ladder and CMB might offer important insights into the origins of the H_0 tension. Gamma-ray bursts (GRBs) are extremely powerful and bright sources that are observed up to very high redshifts, reaching at $z = 8.2$ [27] and $z = 9.4$ [28]. Therefore, GRBs can be used to probe the high-redshift universe beyond SNe Ia. Due to the lack of a low-redshift sample, a fiducial cosmological model should be assumed for calibrating the GRBs luminosity relation in the early cosmological studies [29]. The so-called circularity problem [30] will be encountered. For the purpose to avoid the circularity problem, Liang et al. [31] proposed a cosmological model-independent method to calibrate the luminosity relations of GRBs by using the SNe Ia data [32–36].

On the other side, the observational Hubble data (OHD) using the cosmic chronometers (CC) method from the galactic age differential method [37] has advantages in constraining cosmological parameters and distinguishing DE models. This method allows for Hubble information to be directly derived from observations up to approximately $z \lesssim 2$ [38]. Amati et al. [39] proposed an alternative method to calibrate 193 GRBs (spectral parameters taken from Demianski et al. [40] and references therein) with firmly measured redshift by using the OHD with the CC method. Li et al. [41] calibrated GRBs from the latest OHD using Gaussian Process to construct the GRB Hubble diagram. Xie et al. [42] obtain a larger Ω_M values in the ΛCDM model with GRBs at high redshift, but adding OHD at low redshit removes this trend. Jia et al. [43] indicate that H_0 value is consistent with that measured from the local data at low redshift and drops to the value measured from the CMB at high redshift with SN Ia, OHD and BAO data.

Recently, Hernández-Almada et al. [44] constrained the PEDE and GEDE models with the latest OHD, including non-homogeneous, homogeneous and differential age Hubble data, to obtain values for the deceleration-acceleration transition redshift within a 2σ confidence level. More recently, Liang et al. [45] used a Gaussian Process to calibrate the A118 GRB sample from the Pantheon sample and constrained DE models with GRBs at high redshift and OHD. In this work, we use the cosmology-independent GRBs in Ref. [45] at $1.4 < z \leq 8.2$ and the latest OHD obtained with the CC method which summarized in Ref. [41] at $0.07 < z < 1.965$ to study the two emergent DE models: PEDE and GEDE. We use the information criterion DIC to compare the dark energy models.

The paper is organized as follows: In Section. 2, we summarize the cosmological models to be analyzed. In Section. 3, we briefly describe the observational data sets we used in this work and the corresponding analysis method. The results are shown in Section. 4. Finally, the conclusions are given in Section. 5.

2 Cosmological models

Considering a spatially flat, homogeneous, and isotropic universe and the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, the Friedmann equation can describe the evolution of the Universe with negligible radiation, pressureless matter, and DE:

$$E(a) = \left[\Omega_{\mathrm{m},0} \times a^{-3} + \widetilde{\Omega}_{\mathrm{DE}}(a)\right]^{-\frac{1}{2}}, \tag{1}$$

where the scale factor $a = 1/(1+z)$, $\Omega_{\mathrm{m},0}$ is the current density of matter at redshift $z = 0$. $\widetilde{\Omega}_{\mathrm{DE}}(a)$ is the energy density of the dark energy fluid with respect to the critical energy density at present, with $\rho_{\mathrm{crit},0} = 3H_0^2/8\pi G$ and $\rho_{\mathrm{crit}}(a) = 3H^2(a)/8\pi G$. The present values of the density parameters for pressureless matter are defined as $\Omega_{\mathrm{m},0} = \rho_{\mathrm{m},0}/\rho_{\mathrm{crit},0}$. $\widetilde{\Omega}_{\mathrm{DE}}$ is the density of dark energy, which is defined as:

$$\widetilde{\Omega}_{\mathrm{DE}}(a) = \frac{\rho_{\mathrm{DE}}(a)}{\rho_{\mathrm{crit},0}} = \frac{\rho_{\mathrm{DE}}(a)}{\rho_{\mathrm{crit}}(a)} \times \frac{\rho_{\mathrm{crit}}(a)}{\rho_{\mathrm{crit},0}} = \Omega_{\mathrm{DE},0}(a) \times \frac{H^2(a)}{H_0^2}, \tag{2}$$

where $\Omega_{\mathrm{DE},0}$ is the current density of DE at redshift $z = 0$. Alternatively, this equation can be expressed as a function of redshift z:

$$\widetilde{\Omega}_{\mathrm{DE}}(z) = \Omega_{\mathrm{DE},0} \times \exp\left\{\int_0^z \frac{1+w(z')}{1+z'}\mathrm{d}z'\right\}, \tag{3}$$

The PEDE model [19] has been proposed as a potential alternative to the ΛCDM model without additional degrees of freedom. The DE density at redshift z is given by:

$$\widetilde{\Omega}_{\mathrm{DE}}(z) = \Omega_{\mathrm{DE},0} \times \left[1 - \tanh\left(\log_{10}(1+z)\right)\right]. \tag{4}$$

By assuming a more generalized form of EDE model including extra parameters, the DE density in the GEDE model [24] is given by:

$$\widetilde{\Omega}_{\mathrm{DE}}(z) = \Omega_{\mathrm{DE},0} \times \frac{1 - \tanh\left(\Delta \times \log_{10}\left(\frac{1+z}{1+z_t}\right)\right)}{1 + \tanh\left(\Delta \times \log_{10}(1+z_t)\right)}, \tag{5}$$

where z_t is the transition redshift, which can be derived from $\widetilde{\Omega}_{\mathrm{DE}}(z_t) = \Omega_{\mathrm{m},0}(1+z_t)^3$. In the GEDE model, setting $\Delta = 0$ recovers the ΛCDM model, while setting $\Delta = 1$ yields the PEDE model, with the exception that the authors [24] set $z_t = 0$ for simplicity.

In this work, we also consider the ΛCDM model, the wCDM model and the Chevallier-Polarski-Linder (CPL) parameterization to consider a DE component that depends on redshift [46–49] for comparison. The EoS of all the DE models can be summerized as follows:

$$w(z) = \begin{cases} -1, & \Lambda\text{CDM} \\ w_0, & w\text{CDM} \\ w_0 + \frac{w_a z}{1+z}, & \text{CPL} \\ -\frac{1}{3\ln 10} \times (1 + \tanh\left[\log_{10}(1+z)\right]) - 1, & \text{PEDE} \\ -\frac{\Delta}{3\ln 10} \times \left(1 + \tanh\left[\Delta \times \log_{10}\left(\frac{1+z}{1+z_t}\right)\right]\right) - 1, & \text{GEDE} \end{cases} \tag{6}$$

In order to facilitate model comparison and evaluate their relative merits, several well-established statistical measures were employed. These included the Akaike Information Criterion (AIC) [60], the Bayesian Information Criterion (BIC) [61], and the Deviance Information Criterion (DIC) [62] - all of which have found widespread application in astrophysical research. Since the AIC and BIC criteria employ only the likelihood value at maximum numerically from the Bayesian analysis, one needs to use sufficiently long chains to ensure the accuracy of $\mathcal{L}_{max}$. The quantity DIC, known also as the Bayesian complexity, which focus on assessing the number of parameters that can be usefully constrained by a particular dataset, has been introduced into astrophysics. The use of DIC can provide all the information obtained from the likelihood calls during the maximization procedure. For a quantitative comparison between our proposed in this work, we employ the DIC which is defined as [63]:

$$\text{DIC} = D(\bar{\theta}) + 2p_D = \overline{D(\theta)} + p_D \tag{10}$$

where $D(\theta) = -2ln\mathcal{L}(\theta) + C$, C is a normalized constant depending only on the data which will vanish from any derived quantity, $p_D = \overline{D(\theta)} - D(\bar{\theta})$ is the effective number of model parameters, with the deviance of the likelihood.

3 Observational data

In this section, we describe the observational data used in our analyses for constraining cosmological parameters. For the GRBs sample, we follow the cosmology-independent approach in Liang et al. [45] to calibrate the Amati relation with the A118 GRB sample [50] using the Pantheon SNe Ia sample [4]; and use GRBs data at redshifts $1.4 < z \leq 8.2$ to constrain cosmological models. OHD obtained using the CC method relates the evolution of differential ages of passive galaxies at different redshifts without assuming any cosmological model [51]. We utilize 32 updated OHD measurements compiled from Ref. [41], covering a redshift range of $0.07 < z < 1.965$, which consists of 15 correlated measurements with the corresponding covariance matrix provided by Moresco et al. [52], and 17 uncorrelated measurements with the latter sourced from [53–55]. The cosmology-independent 98 GRBs at $1.4 < z \leq 8.2$ and 32 OHD $0.07 < z < 1.965$ are showed in Fig. 1.

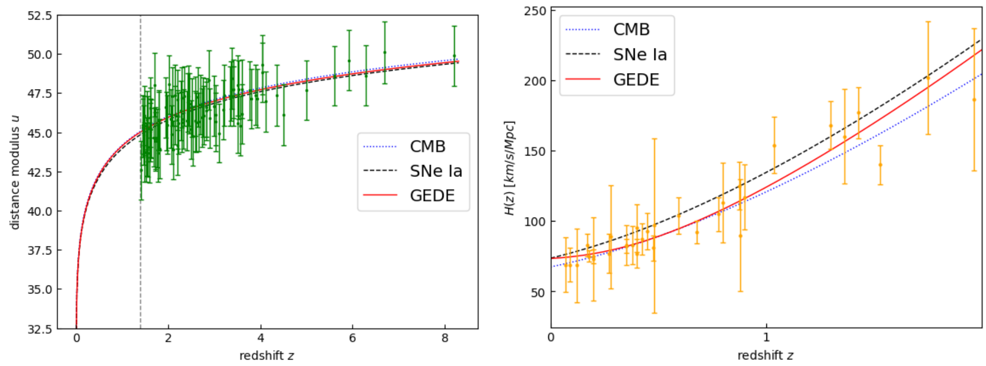

Fig. 1 The cosmology-independent 98 GRBs at $1.4 < z \leq 8.2$ (*left*) and 32 OHD $0.07 < z < 1.965$ (*rihgt*). The red solid curves present the predicted values from the best values of GEDE model with GRBs and OHD, respectively. The blue dotted curve and the black dashed curve are the predicted values of distance modulus for a flat ΛCDM model from SNe Ia, and CMB, respectively.

The cosmological parameters are fitted by minimizing the χ^2 method:

$$\chi^2_{\rm GRB} = \sum_{i=1}^{N} \left[\frac{\mu_{\rm obs}(z_i) - \mu_{\rm th}(z_i; p, H_0)}{\sigma_{\mu_i}} \right]^2 \tag{7}$$

where $N = 98$ represents the number of GRBs at high-redshift, σ_{μ_i} is the uncertainty associated with the observed distance modulus, $\mu_{\rm th}$ denotes the theoretical distance modulus which determined by the cosmological parameters p with DE models and H_0. To constrain the dark energy models using the OHD data, the corresponding $\chi^2_{\rm OHD}$ is given by:

$$\chi^2_{\rm OHD} = \sum_{i=1}^{17} \left[\frac{H_{\rm obs}(z_i) - H_{\rm th}(z_i; p, H_0)}{\sigma_{H_i}} \right]^2 + \Delta\hat{H}^T C_H^{-1} \Delta\hat{H} \tag{8}$$

where σ_{H_i} represents the observed uncertainty of the 17 uncorrelated measurements, $\Delta\hat{H} = H_{\rm obs}(z) - H_{\rm th}(z; p, H_0)$ represents the difference vector between the observed data and the theoretical values for the 15 correlated measurements, and C_H^{-1} is the inverse of the covariance matrix. The total χ^2 statistic, combining GRB and OHD, is given by:

$$\chi^2_{\rm tot} = \chi^2_{\rm GRB} + \chi^2_{\rm OHD} \tag{9}$$

4 Results

In this section, we estimate and compare the parameters of the standard ΛCDM model, the wCDM model, the CPL, the PEDE model and the GEDE model using cosmological observation data from GRBs and OHD. We adopt a Bayesian statistical approach for parameter inference and model selection. Through the minimization of the χ^2 value, we can obtain the best-fit parameter estimates. We employ the *emcee* Python module

[56] in the lmfit python library [57]. Furthermore, we utilize the GETDIST package [58] to analyze the sampled chains.

Table 1 Constraints at 68% confidence-level errors on the cosmological parameters for the different tested dark energy models with GRBs-only, OHD-only and GRBs + OHD. And at 95% confidence-level errors on the Δ for GEDE.

Parameters	H_0	Ω_m	w_0	w_a	Δ	z_t^*	χ^2_{md}	ΔDIC
GRBs-only								
ΛCDM	$72.0^{+10.0}_{-20.0}$	$0.50^{+0.18}_{-0.36}$	-	-	0	$0.060^{+0.370}_{-0.500}$	26.831	0
wCDM	$70.0^{+8.0}_{-20.0}$	$0.50^{+0.24}_{-0.36}$	-0.98 ± 0.55	-	-	$-0.120^{+0.570}_{-0.490}$	26.951	+0.368
CPL	$69.0^{+9.0}_{-20.0}$	$0.53^{+0.39}_{-0.34}$	$-1.03^{+0.42}_{-0.83}$	$-0.20^{+1.30}_{-2.30}$	-	$-0.110^{+0.580}_{-0.360}$	26.954	+0.625
PEDE	$73.0^{+10.0}_{-20.0}$	$0.52^{+0.22}_{-0.36}$	-	-	1	0.020 ± 0.360	26.884	−0.195
GEDE	$73.0^{+10.0}_{-20.0}$	$0.55^{+0.20}_{-0.31}$	-	-	$4.9 \pm 2.9(^{+4.8}_{-4.6})$	$-0.001^{+0.220}_{-0.250}$	26.942	+0.204
OHD-only								
ΛCDM	68.8 ± 4.1	$0.324^{+0.048}_{-0.074}$	-	-	0	0.290 ± 0.120	14.526	0
wCDM	$70.2^{+5.6}_{-6.7}$	$0.294^{+0.084}_{-0.060}$	$-1.15^{+0.46}_{-0.57}$	-	-	$0.220^{+0.180}_{-0.140}$	15.080	+0.043
CPL	$70.5^{+5.7}_{-6.8}$	$0.305^{+0.100}_{-0.072}$	$-1.17^{+0.40}_{-0.66}$	$-0.30^{+1.30}_{-2.20}$	-	$0.270^{+0.140}_{-0.200}$	15.160	+0.322
PEDE	69.9 ± 4.2	$0.332^{+0.046}_{-0.068}$	-	-	1	0.235 ± 0.099	14.497	−0.064
GEDE	72.4 ± 4.8	$0.334^{+0.038}_{-0.063}$	-	-	$3.7^{+1.4}_{-3.5}(^{+5.4}_{-3.8})$	$0.185^{+0.062}_{-0.092}$	14.752	+0.589
GRBs + OHD								
ΛCDM	69.9 ± 4.0	$0.325^{+0.049}_{-0.070}$	-	-	0	0.290 ± 0.120	43.250	0
wCDM	$71.2^{+5.2}_{-6.2}$	$0.298^{+0.081}_{-0.057}$	$-1.14^{+0.53}_{-0.43}$	-	-	$0.220^{+0.170}_{-0.140}$	43.682	+0.034
CPL	71.9 ± 6.1	$0.311^{+0.092}_{-0.067}$	$-1.18^{+0.37}_{-0.67}$	$-0.40^{+1.20}_{-2.30}$	-	$0.265^{+0.094}_{-0.190}$	43.609	+0.409
PEDE	71.0 ± 4.1	$0.335^{+0.045}_{-0.066}$	-	-	1	0.231 ± 0.095	43.221	−0.190
GEDE	73.4 ± 4.7	$0.335^{+0.040}_{-0.057}$	-	-	$3.6^{+1.3}_{-3.4}(^{+5.1}_{-3.7})$	$0.184^{+0.059}_{-0.089}$	43.499	+0.606

Note: The last column of the table display the ΔDIC values relative to the ΛCDM model, derived from the same data combinations. χ^2_{md} represents the median value of χ^2. The parameter z_t^* is not a free parameter.

The results of cosmological parameters with 1σ uncertainties constraint with GRBs-only, OHD-only and GRBs + OHD for five DE models are provided in Table 1. For the case with GRBs-only, we obtain H_0 and Ω_m with the large error bars which indicate that the cosmological parameters are not well-constrained with this datasets; the ΛCDM model ($w_0 = -1, w_a = 0$) are consistent with the inferred value of $w_0 = -0.98 \pm 0.55$ for the wCDM model and $w_0 = -1.03^{+0.42}_{-0.83}, w_a = -0.20^{+1.30}_{-2.30}$ for the CPL model within 1σ uncertainty. For the case with OHD-only, we find that the value of H_0 for the PEDE model ($H_0 = 69.90 \pm 4.20\,\mathrm{km\,s^{-1}Mpc^{-1}}$) is lower than that of the GEDE model ($H_0 = 72.40 \pm 4.80\,\mathrm{km\,s^{-1}Mpc^{-1}}$), which shows agreement with the SH0ES measurement [17, 18]. For the case with GRBs + OHD, the measured H_0 ranges from $69.90 \pm 4.00\,\mathrm{km\,s^{-1}Mpc^{-1}}$ (ΛCDM) to $73.40 \pm 4.70\,\mathrm{km\,s^{-1}Mpc^{-1}}$ (GEDE). When the OHD is combined with GRBs, we find the constraints results on H_0 and Ω_m can be significantly improved and the mean values shifts in the same direction, though the overall effect is not very large. From Table 1, we can see that for all models, the constraints on H_0 and Ω_m from OHD and GRBs + OHD are well consist with each other at 1σ CL, but in agreement with the constraint from GRBs at about 2σ. Interestingly, the constraints for the wCDM model and CPL model are not well-constrained and exhibit results distinct from the other models.

The statistical measures of the model comparison for the three datasets are also presented in Table 1. The PEDE model outperforms the ΛCDM model in both the GRBs-only and OHD-only datasets, with $\Delta\text{DIC} = -0.195$ and $\Delta\text{DIC} = -0.064$, respectively. This trend continues in the combined GRBs + OHD dataset, where the PEDE model surpasses not only the ΛCDM model but also the wCDM and CPL models across all evaluation measures. However, the GEDE model does not exhibit clear evidence of superiority over the ΛCDM, wCDM and CPL models in any of the datasets. It is noteworthy that the analysis was conducted without assuming any hard-cut prior on the Hubble constant (H_0), ensuring an unbiased comparison of the models. In summary, the PEDE model consistently demonstrates a better fit to the data compared to the ΛCDM model, as evidenced by its lower DIC values. In contrast, the wCDM and CPL parameterization models perform poorly in terms of DIC when compared to the ΛCDM model, highlighting the PEDE model's superiority in describing the observations across all three datasets.

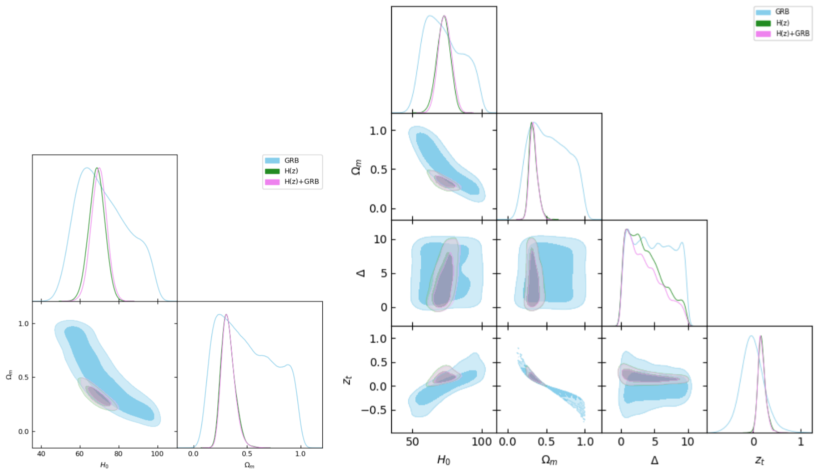

Fig. 2 Two-dimensional plots and 1D marginalized distributions with 1σ and 2σ contours of cosmological parameters (H_0 and Ω_m) for the ΛCDM model (left plot) and cosmological parameters (H_0, Ω_m and Δ) in the framework of GEDE (right plot) from GRBs-only, OHD-only, GRBs + OHD. Note that z_t is not a free parameter and is shown for clarity.

In Fig. 2, we show the constrained results of the cosmological parameters for the ΛCDM and GEDE model with GRBs-only, OHD-only, and GRBs + OHD datasets. We find the constraints on H_0 are all in agreement with each other at 1σ confidence level and also agree with the local results from the SH0ES collaboration [59]. For the free parameter of the GEDE model, we can find that the results with GEDE exclude PEDE and ΛCDM in 1σ and with large error for GRBs-only case. $\Delta = 0$ is in agreement at about 1.7σ, and $\Delta = 1$ is at about 1.3σ. For OHD-only and GRBs + OHD datasets, we get the result with tight error bars and that PEDE is preferred, namely, Δ close to 1. We get $\Delta = 1$ is in agreement at about 1.9σ, $\Delta = 0$ is at about 2.6σ for OHD-only and $\Delta = 1$ is in agreement at about 2σ, $\Delta = 0$ is at about 2.8σ for GRBs + OHD.

ΛCDM are excluded in 2σ. Interestingly, the derived parameter z_t of the GEDE model ($z_t = 0.185^{+0.062}_{-0.092}$) with OHD-only and ($z_t = 0.184^{+0.059}_{-0.089}$) with GRBs + OHD are in agreement with the result of Hernández-Almada et al. ($z_t = 0.174^{+0.083}_{-0.064}$) from OHD sample [44]. Our result are aslo consist with Liu et al. [23].

In Fig. 3, we present the constraints on H_0 and Ω_m for the ΛCDM, wCDM, CPL, PEDE and GEDE models using the combined OHD and GRBs. We can find that the PEDE and GEDE models yield higher values with a clear trend for both parameters of H_0 and Ω_m compared to ΛCDM. Furthermore, the GEDE model exhibits even more higher values than the PEDE model. These findings suggest that the EDE models have the potential to alleviate the H_0 tension. It is evident that the PEDE model and GEDE model can yield a higher best-fit value of H_0 than the ΛCDM model when considering the GRBs, OHD and GRBs + OHD cases. These results are more consistent with those from the SH0ES collaboration [59].

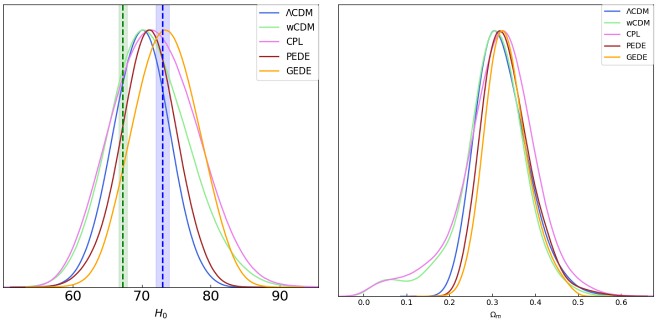

Fig. 3 The constraints for H_0 (*left*) and Ω_m (*right*) with the ΛCDM, wCDM, CPL, PEDE and GEDE model from the GRBs + OHD data. The blue line is represent the result from ΛCDM, the brown and orange lines represent the result from PEDE and GEDE respectively. The blue shadows show the H_0 results with 1σ uncertainty from Riess et al. [59], the green shadows show the H_0 results with 1σ uncertainty from Planck CMB observations [12].

In Fig. 4, we show the evolution of dark energy density $\widetilde{\Omega}_{\mathrm{DE}}(z)$ as a function of redshift z. We can see an emergent dark energy behavior from GRBs + OHD data, and the cosmological constant is outside the 2σ confidence limits.

We find our results are compatible with the previous works of Li et al. [19, 24], where the authors observed that the value of H_0 derived from the ΛCDM and CPL parameterization models is close to the CMB prediction, regardless of whether the dataset includes CMB data or not. The authors also found that the value of H_0 aligns closely with the local measurement value obtained by the SH0ES collaboration when assuming 1σ and 2σ priors for H_0 taken from the SH0ES result. Our result is compatible with their findings, but it is important to emphasize that we perform our analysis without assuming any hard-cut prior on H_0.

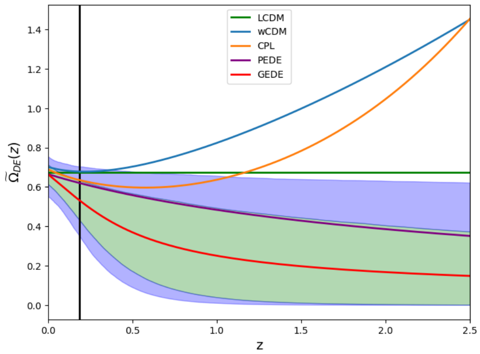

Fig. 4 The evolution of dark energy density $\widetilde{\Omega}_{\rm DE}(z)$. In this figure shows the evolution in linear scales of z from 0 to 2.5. The green and dark blue lines are the 1σ and 2σ confidence ranges of the GEDE model fitting OHD + GRB data. The green, blue, orange, purple and red solid lines are the best-fit results from the ΛCDM, wCDM, CPL, PEDE and GEDE models, respectively. The OHD + GRB data suggest an emergent dark energy behavior, while the cosmological constant is very much outside the confidence limits. The vertical lines display the mean values of z_t from GRBs + OHD.

5 Conclusion

We have investigated the viability of the PEDE and the GEDE models with cosmology-independent observational data including GRBs and OHD samples in the mid-redshift region between the local the distance ladder SN Ia and CMB. Considering OHD only and GRBs + OHD, PEDE and GEDE yield relatively higher values for H_0 compared to the ΛCDM model; for GRBs only case, the constant of H_0 form ΛCDM is close to that from PEDE and GEDE. All models can infer Ω_m very well, with values close to the expected ones and with small errors. The GRBs + OHD datasets appear to provide much better constraints on the DE parameters and the value of the Hubble constant. We compare our constrained result of H_0 with CMB measurements from Planck [11, 12] and H_0 results from local observations of Cepheids [14–16].

We also find that PEDE and GEDE derive higher H_0 compare to ΛCDM, which support the viability of EDE models as a description of dark energy behavior and provide new evidence for their potential as an important supplement and possible alternative to the ΛCDM model. Our results are consistent with previous analyses [19, 20, 23, 24, 44], which indicate that EDE models are at least competitive with the ΛCDM model in describing the accelerated expansion of the universe and can alleviate the H_0 tension problem.

In conclusion, our work demonstrates that the EDE models can better represent the effective behavior of DE compared to the ΛCDM model and can significantly reduce tensions in the estimation of the Hubble constant. Given the challenges faced by the standard model, this implies that EDE models can be competitive cosmological models. To further test the validity of EDE models, future theoretical explorations and observational verifications are needed, particularly precise measurements of the evolution of the Hubble parameter at higher redshifts and more in-depth studies of the energy components at different epochs in the early universe. Only with support from multiple lines of evidence can we ultimately determine the status of EDE models in explaining the accelerated expansion of the universe.

ACKNOWLEDGMENTS

This project was supported by the Guizhou Provincail Science and Technology Foundation: QKHJC-ZK[2021] Key 020 and QKHJC-ZK[2024] general 443. X. Li was supported by NSFC No. 12003006, Science Research Project of Hebei Education Department No. BJK2024134 and the fund of Hebei Normal University No. L2020B02.

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