Testing the Phenomenological Interacting Dark Energy Model with Gamma-Ray Bursts and Pantheon+ type Ia Supernovae

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Full Text

Testing the Phenomenological Interacting Dark Energy Model with Gamma-Ray Bursts and Pantheon+ type Ia Supernovae

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Abstract

In this paper, we utilize recent observational data from gamma-ray bursts (GRBs) and Pantheon+ supernovae Ia (SNe Ia) samples to explore the interacting dark energy (IDE) model in a phenomenological scenario. Results from GRBs alone, SNe Ia and GRBs+SNe Ia indicate that the energy is transferred from dark energy to dark matter and the coincidence problem is alleviated. The value of H_0 from GRBs+SNe Ia in the IDE scenario shows agreement with the SH0ES measurement. Considering the age estimate of the quasar APM 08279+5255 at $z = 3.91$, we find that the phenomenological IDE scenario can predict a cosmic age greater than that of the ΛCDM model, thus the cosmic age problem can be alleviated.

Key words: cosmology: observations –(cosmology:) dark energy –(cosmology:) cosmological parameters

1. Introduction

Observations of type Ia Supernovae (SNe Ia) have unequivocally demonstrated that our universe is experiencing accelerated expansion (Riess et al. 1998; Perlmutter et al. 1999; Astier et al. 2006; Hicken et al. 2009; Amanullah et al. 2010). Additional supports come from cosmic microwave background (CMB) radiation (Spergel et al. 2003, 2007; Komatsu et al. 2009, 2011) and large-scale structure (Tegmark et al. 2004; Eisenstein et al. 2005; Percival et al. 2010). However, the standard ΛCDM model which assumes dark energy (DE) is a cosmological constant Λ encounters the cosmological constant problem (Weinberg 1989; Carroll et al. 1992), encompassing the fine-tuning and cosmic coincidence issues. Moreover, the H_0 tension with the discrepancy between local measurements by SNe Ia (Riess et al. 2016, 2018, 2019, 2022a, 2022b) and early Universe measurements from CMB observations (Planck Collaboration et al. 2016, 2020) under the ΛCDM model exceeding 5σ represents a significant challenge in modern cosmology.

To address or mitigate the coincidence problem, many alternative dynamic models of DE have been proposed (Ratra & Peebles 1988; Caldwell et al. 1998; Armendariz-Picon et al. 2001; Bento et al. 2002; Caldwell 2002; Chiba 2002; Caldwell et al. 2003; Feng et al. 2005). The interacting dark energy (IDE) models, which involve potential interactions between DE and dark matter (DM), have also been proposed and investigated to alleviate the coincidence problem (Amendola 2000; Zimdahl et al. 2001; Chimento et al. 2003; Guo & Zhang 2005; Guo et al. 2005; Wei & Zhang 2007a, 2007b; Cai & Su 2010; Li et al. 2014; Gonzalez et al. 2019). Many studies suggest that interactions between DE and DM can lead to an increased value of H_0, potentially alleviating the tension between measurements from the Planck collaboration (within the ΛCDM paradigm) and the SH0ES collaboration (Kumar & Nunes 2016; Arevalo et al. 2017; Di Valentino et al. 2017; Kumar & Nunes 2017; Gonzalez et al. 2018; Yang et al. 2018; Kumar et al. 2019; Pan et al. 2019, 2020; von Marttens et al. 2019; Yang et al. 2020). Recently, Cheng et al. (2021) investigated the possible interaction between DE and weakly interacting massive particle DM using observational data in cosmology. Wang (2022) found that the combined data from Pantheon+, CMB, baryon acoustic oscillations (BAOs), and the observational Hubble data (OHD) suggest energy transfer from DE to DM at 1.85σ confidence level; Zhao et al. (2023) used the mock Fast radio bursts to constrain the dimensionless coupling parameter in four phenomenological IDE models; Hou et al. (2023) constrained four phenomenological IDE models using the joint observation of gravitational wave (GW) and gamma-ray bursts (GRBs); Li & Zhang (2023) developed a full numerical routine to solve the background and perturbation equations of the IDE models. Li et al. (2024) simulated GW data of four detection strategies to perform cosmological analysis in four phenomenological IDE models. Halder et al. (2024) considered interaction scenarios that depend on the intrinsic nature of DE and DM, extending the unidirectional energy flow assumption to allow for bidirectional energy flow with sign shifting interaction functions.

The IDE models can be explored phenomenologically by considering the ratio of the energy densities of dark energy to matter as $r \equiv \rho_X \propto \rho_m a^{\xi}$, where the variable ξ measures the

severity of the coincidence problem (Dalal et al. 2001). The interaction term can be obtained by $Q = -H\rho_m(\xi + 3w_X)$ in a flat FLRW universe, where w_X represents the equation of state for DE. The condition $\xi + 3w_X \neq 0$ denotes the interacting scenario. Chen et al. (2010) constrained the phenomenological model utilizing SNe Ia, CMB, and BAO; Cao et al. (2011) investigated observational constraints for this phenomenological interacting scenario by integrating OHD with the joint data. More recently, Zheng et al. (2022) found that the simulated GW can decrease the uncertainty associated with H_0 from the joint sample in the frameworks of two typical dynamical models: the $w_0 w_a$CDM model and this phenomenological model.

Another possible difficulty for the ΛCDM model is related to the age problem. This issue arises from observations of certain astrophysical objects: the quasar APM 08279+5255 at $z = 3.91$ with a rough estimate of $t_{\mathrm{QSO}} = 2.0 \sim 3.0$ Gyr (Hasinger et al. 2002), and 1σ lower age limit 1.8 Gyr (Friaça et al. 2005), which appear to be older than the universe itself according to the ΛCDM model. The cosmic age problem relative to the quasar APM 08279+5255 has been investigated in various studies (Sethi et al. 2005; Wei & Zhang 2007c; Cui & Zhang 2010; Yang & Zhang 2010; Chimento et al. 2013; Yu & Wang 2014; Yan et al. 2015).

The cosmic age problem of quasar APM 08279+5255 can also be investigated in interacting scenarios. Wang & Zhang (2008) showed that introducing dark energy alone does not solve the cosmic age problem when considering the quasar APM 08279+5255, suggesting that the potential interaction between dark energy and dark matter could offer a solution. Wang et al. (2010) found that 5 globular clusters and the quasar exhibit an age discrepancy with the ΛCDM model at a confidence level exceeding 2σ, even when considering observational constraints from SNe Ia, BAO, CMB, and H_0 measurements; considering IDE models can extend the cosmic age, however, IDE models still struggle to fully resolve the age problem. More recently, Zarandi & Ebrahimi (2022) discussed the cosmic age problem within the ghost dark energy model in the presence of three types of the sign-changeable interaction terms.

Observational data sets have played a crucial role in constraining cosmology. SNe Ia data span only up to a redshift of approximately $z \sim 2$, while CMB data pertain to redshifts near $z \sim 1100$. Therefore, cosmological data in the intermediate region could potentially provide vital understandings of the origins of the coincidence problem, H_0 tension, and the cosmic age problem. GRBs are known to reach a higher maximum observable redshift, approximately $z \sim 10$ (Cucchiara et al. 2011). Due to the scarcity of samples at low redshift, a fiducial cosmological model was necessary to presuppose for the calibration of the GRBs luminosity relation in the early research (Dai et al. 2004; Schaefer 2007). Liang et al. (2008) introduced a cosmological model-independent method for calibrating the luminosity relations of GRBs by utilizing data from SNe Ia. On the other hand, the simultaneous method (Amati et al. 2008) has been also put forward to avoid the circularity problem by fitting the parameters of the correlation and cosmological models simultaneously. Amati et al. (2019) proposed an alternative approach for calibrating the GRB relation using OHD by the cosmic chronometers (CC) method. Therefore, GRBs data can be employed to place constraints on cosmological models without the circularity problem[1] (Wei 2010a, 2010b; Liang et al. 2010, 2011; Wang et al. 2016; Dainotti & Del Vecchio 2017; Demianski et al. 2017a, 2017b; Dainotti & Amati 2018; Dirirsa et al. 2019; Luongo & Muccino 2020, 2021a, 2021b; Montiel et al. 2021; Liu et al. 2022; Dainotti et al. 2023). It should be noted that the classification of GRBs is important for the calibration of GRB relations. If GRBs can be treated as standard candles, only a small fraction of GRBs can be suitable for cosmological use. See e.g., Wang et al. (2022) and Hu et al. (2021) for recent progress focused on specific GRB types to improve their standardization and enhance their utility in cosmology.

More recently, Khadka et al. (2021) made a compilation of a data set comprising 118 GRBs with the smallest intrinsic dispersion from a broader set of 220 GRBs. Liang et al. (2022) and Li et al. (2023) calibrated these GRB data using a Gaussian Process, from the Pantheon sample (Scolnic et al. 2018) or the most recent OHD by the CC method (Moresco et al. 2022). Wang et al. (2024) investigate the phenomenologically emergent dark energy model with GRBs and OHD at intermediate redshift. In this paper, our goal is to test the phenomenological interacting scenario[2] from cosmology-independent GRBs at redshifts ranging from 1.4 to 8.2 (Li et al. 2023) and the Pantheon+ sample, which is the most recent compilation of SNe Ia including 1701 light curves from 1550 unique data at redshifts ranging from 0.001 to 2.26 (Scolnic et al. 2022). To further explore the cosmic age problem, we incorporate the quasar APM 08279+5255 at redshift $z = 3.91$ as an extra data point. The rest of the paper is organized as follows: Section 2 provides an overview of the phenomenological IDE model. The observational data adopted in this study are described in Section 3. Constraints from the observational data are given in Section 4. We give a brief conclusion in Section 5.

2. Overview of the Phenomenological Interacting Model

In this paper, we explore the possibility of DE and matter engage in an energy exchange through an interaction term

denoted as Q

[1] For a comprehensive review of the circularity problem in GRB cosmology, see Wang et al. (2015).

[2] In this work, we use ξIDE to represent this phenomenological interaction model.

$$\begin{aligned}\dot{\rho}_X + 3H\rho_X(1+w_X) = -Q,\\ \dot{\rho}_m + 3H\rho_m = Q.\end{aligned} \tag{1}$$

The phenomenological model adopts an assumption that the ratio of the dark energy to matter densities is (Dalal et al. 2001)

$$\rho_X \propto \rho_m a^{\xi}, \tag{2}$$

values of $\xi = 3$ and $\xi = 0$ are associated with the ΛCDM model and a self-similar solution that is free from the coincidence problem, respectively; while $0 < \xi \leq 3$ indicates a less severe coincidence problem (Pavon et al. 2004). Considering the phenomenological model in a flat FLRW universe with $\Omega_{X0} + \Omega_{m0} = 1$, we can derive the interaction term,

$$Q = -H\rho_m(\xi + 3w_X)\Omega_X, \tag{3}$$

where $\Omega_X = \dfrac{1-\Omega_{m0}}{(1-\Omega_{m0}) + \Omega_{m0}(1+z)^{\xi}}$, the case $\xi + 3w_X = 0$ (which implies $Q = 0$) corresponds to the standard cosmology without any interaction between dark energy and matter. Conversely, $\xi + 3w_X \neq 0$ indicates the non-standard cosmology. Furthermore, when $\xi + 3w_X > 0$ ($Q < 0$), it suggests that energy is transferred from matter to DE, which tends to exacerbate the coincidence problem. Oppositely, if $\xi + 3w_X < 0$ ($Q > 0$), it indicates that the energy is transferred from DE to DM, which could potentially mitigate the coincidence problem. The $H(z)$ function of the phenomenological model can be expressed as (Cao et al. 2011)

$$H(z) = H_0\sqrt{(1+z)^3\left[\Omega_{m0} + (1-\Omega_{m0})(1+z)^{-\xi}\right]^{-3w/\xi}}. \tag{4}$$

For comparison, we also utilize the Chevallier–Polarski–Linder (CPL) model (Chevallier & Polarski 2001; Linder 2003), where dark energy is represented as evolving with redshift through the parameterization $w = w_0 + w_a z/(1+z)$. The ΛCDM model corresponds to $w_0 = -1$, $w_a = 0$. The $H(z)$ function of them can be expressed as

$$H(z) = H_0\sqrt{\Omega_{m0}(1+z)^3 + (1-\Omega_{m0})(1+z)^{3(1+w_0+w_a)}e^{-\frac{3w_a z}{1+z}}}. \tag{5}$$

To evaluate the efficacy of various models when applied to diverse data set combinations, we proceed to quantify the variances in the Akaike information criterion (AIC; Akaike 1974, 1981) and the Bayesian information criterion (BIC; Schwarz 1978), as defined by the following equations

$$\mathrm{AIC} = 2p - 2\ln(\mathcal{L}_{\max}), \tag{6}$$

$$\mathrm{BIC} = p\ln N - 2\ln(\mathcal{L}_{\max}). \tag{7}$$

where p is the number of parameters in the model, N is the sample size of the observational data combination, and $\mathcal{L}_{\max}$ is the maximum likelihood of the model. The values of ΔAIC and ΔBIC for each model are given by AIC $= \chi^2_{\min} + 2\Delta n$, and BIC $= \chi^2_{\min} + \Delta n \ln N$. They represent the differences in AIC and BIC, respectively, when compared to the values obtained for the ΛCDM model.

3. Observational Data

The recent observations of GRB sample (Khadka et al. 2021) and the latest SNe Ia sample (Scolnic et al. 2022) are utilized in our cosmological analysis. For the GRBs sample, we follow the cosmology-independent approach in Li et al. (2023) to calibrate the Amati relation using the A118 GRB sample[3] using the 32 updated OHD measurements. We utilize GRB data at $z > 1.4$ to constrain on cosmological models, the χ^2_{GRB} function is defined as:

$$\chi^2_{\mathrm{GRB}} = \sum_{i=1}^{N} \left[\frac{\mu_{\mathrm{obs}}(z_i) - \mu_{\mathrm{th}}(z_i; p, H_0)}{\sigma_{\mu_i}} \right]^2, \tag{8}$$

where $N = 98$, $\mu_{\mathrm{th}}(z_i; p, H_0)$ represents the theoretical distance modulus of the model at redshifts z_i, H_0 is the Hubble constant, p denotes the cosmological parameter space, $\mu_{\mathrm{obs}}(z_i)$ and σ_{μ_i} correspond to the observed value and the error, respectively.

The SNe Ia sample used in this study is the Pantheon+ sample, which comprises 1701 SNe Ia light curves observed from 1550 distinct SNe, spanning a redshift range of 0.001-2.26 (Brout et al. 2022; Scolnic et al. 2022). This data set includes major contributions from various sources, including CfA1 (Riess et al. 1999), CSP DR3 (Krisciunas et al. 2017), DES (Brout et al. 2019), PS1 (Scolnic et al. 2018), SDSS (Sako et al. 2018) and SNLS (Betoule et al. 2014). The optimal values for the cosmological parameters are derived by minimizing χ^2_{SNe}

$$\chi^2_{\mathrm{SNe}} = \Delta\mu C^{-1}_{\mathrm{stat+syst}} \Delta\mu^T, \tag{9}$$

where $\Delta\mu$ denotes the discrepancy between the observed distance modulus μ_{obs} and its theoretical distance modulus μ_{th}:

[3] We use the A118 GRB sample from the A220 GRB sample used in Khadka et al. (2021) with the higher qualities appropriate to investigate cosmology.

$$\Delta\mu = \mu_{\rm obs}(z_i) - \mu_{\rm th}(z_i; p, H_0). \tag{10}$$

The corresponding expression for $\mu_{\rm th}$ can be given by:

$$\mu_{\rm th}(z_i; p, H_0) = m - M = 5\log_{10}\frac{d_L(z_i; p, H_0)}{\rm Mpc} + 25, \tag{11}$$

here, z_i indicates the peculiar-velocity-corrected CMB-frame redshift of each SNe Ia (Carr et al. 2022), p represents the cosmological parameters, m denotes the apparent magnitude of the source, M is the absolute magnitude, and d_L is the luminosity distance, defined as

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{H(z')}, \tag{12}$$

Figure 1. Constraints on the cosmological parameters of the ΛCDM model (left), the CPL model (middle), and the ξIDE model (right) with GRBs alone.

Table 1

Constraints on Cosmological Parameters Ω_m, h, w_X, ξ, w_0 and w_a for the ΛCDM Model, the CPL Model, and the ξIDE Model Using GRBs ($z > 1.4$), SNe Ia, and GRBs+SNe Ia

Parameters	Ω_m	h	w_X	ξ	w_0	w_a	$-2\ln\mathcal{L}_{\max}$	ΔAIC	ΔBIC
GRBs									
ΛCDM	$0.369^{+0.070}_{-0.100}$	0.7	···	···	···	···	43.145	···	···
CPL	$0.33^{+0.17}_{-0.12}$	0.7	···	···	$-0.87^{+0.84}_{-0.40}$	0.99 ± 0.56	43.212	4.067	9.238
ξIDE	$0.45^{+0.28}_{-0.20}$	0.7	$-1.56^{+1.10}_{-0.31}$	$3.8^{+2.1}_{-3.8}$	···	···	43.383	4.238	9.409
SNe Ia									
ΛCDM	0.358 ± 0.013	0.7288 ± 0.0019	···	···	···	···	1821.892	···	···
CPL	$0.338^{+0.072}_{-0.043}$	0.7259 ± 0.0024	···	···	$-0.849^{+0.120}_{-0.098}$	$-0.87^{+0.85}_{-0.32}$	1820.629	2.737	13.615
ξIDE	0.42 ± 0.23	0.7266 ± 0.0023	$-1.27^{+0.73}_{-0.34}$	$2.12^{+0.43}_{-1.40}$	···	···	1995.103	177.211	188.089
GRBs+SNe Ia									
ΛCDM	0.357 ± 0.013	0.7289 ± 0.0019	···	···	···	···	1865.338	···	···
CPL	$0.326^{+0.071}_{-0.046}$	0.7258 ± 0.0024	···	···	$-0.831^{+0.110}_{-0.091}$	$-0.80^{+0.79}_{-0.30}$	1863.671	2.333	12.343

Parameters	Ω_m	h	w_X	ξ	w_0	w_a	$-2\ln\mathcal{L}_{\max}$	ΔAIC	ΔBIC
ξIDE	$0.525^{+0.280}_{-0.099}$	0.7266 ± 0.0022	$-1.55^{+1.00}_{-0.57}$	$1.78^{+0.31}_{-1.10}$	$\cdots$	$\cdots$	2035.557	243.557	254.501

where c represents the speed of light. The complete covariance matrix for Pantheon+ sample is given by Brout et al. (2022):

$$C_{\text{stat+syst}} = C_{\text{stat}} + C_{\text{syst}}, \tag{13}$$

where C_{stat} and C_{syst} refer to the statistical and systematic covariance matrices, respectively. The data sets and $C_{\text{stat+syst}}$ can be obtained online.[4] The total χ^2_{total} for the combined GRBs and SNe Ia data is given by $\chi^2_{\text{total}} = \chi^2_{\text{GRB}} + \chi^2_{\text{SNe}}$. The MCMC method, facilitated by the Python package emcee (Foreman-Mackey et al. 2013), is employed for the minimization of the chi-square function χ^2.

4. Constraints On Cosmological Models

Since GRB data alone cannot constrain H_0 due to the degeneracy with the correlation intercept parameter, we follow previous works (Khadka et al. 2021; Liang et al. 2022) and fix $H_0 = 70$ km s^{-1} Mpc^{-1} for the case of GRBs alone. The results are presented in Figure 1 and summarized in Table 1. For the CPL model, the constraint on the parameter w_a using GRBs alone indicates a possible DE evolution ($w_a \neq 0$) within the 1σ confidence region. For the ξIDE model, the constraint results for w_X and ξ suggest: $\xi + 3w_X < 0$ with GRBs alone. This finding is consistent with recent work (Zheng et al. 2022); however, this result is different from previous studies, which

Figure 2. Constraints on the cosmological parameters of the ΛCDM model (left), the CPL model (middle), and the ξIDE model (right), with SNe Ia and GRBs + SNe Ia.

found $\xi + 3w_X > 0$ to be slightly preferred (Guo et al. 2007; Chen et al. 2010; Cao et al. 2011). We find that our results for the ΛCDM model, the wCDM model, and the CPL model using GRBs alone are compatible with the previous work of Li et al. (2023).

We also consider the joint constraints using GRBs and the Pantheon+ sample. The best-fit values, with the 1σ confidence level for the parameters obtained from SNe Ia and GRBs + SNe Ia, are shown in Figure 2 and summarized in Table 1. We find that GRBs + SNe Ia provide stronger constraints on the parameters (Ω_m, h, w_X and ξ) within the frameworks of the ΛCDM, CPL, and ξIDE models, while GRBs alone give weak constraints on all parameters. We find that $\xi+3w_X < 0$ with SNe Ia and GRBs + SNe Ia for the ξIDE model, which is consistent with the GRBs-only case. For the value of the Hubble constant, our result

[4]https://github.com/PantheonPlusSH0ES/DataRelease

with GRBs + SNe Ia for the ξIDE model agrees with that reported by SHOES (Riess et al. 2022a), ($H_0 = 73.01 \pm 0.99$ km s^{-1} Mpc^{-1}), at 0.35σ. Additionally, our result is in agreement with those obtained by Hu et al. (2024), ($H_0 = 72.83 \pm 0.23$ km s^{-1} Mpc^{-1}), and Wang (2022), ($H_0 = 73.5^{+8.1}_{-10.0}$ km s^{-1} Mpc^{-1}), with the 1σ error of h reduced. For the ΛCDM model with SNe Ia, our result is consistent with Brout et al. (2022), ($H_0 = 73.6 \pm 1.1$ km s^{-1} Mpc^{-1}), and Dahiya & Jain (2023), ($H_0 = 73.500^{+1.013}_{-0.978}$ km s^{-1} Mpc^{-1}), except for a reduced 1σ error for H_0. This is mainly due to the application of the standardized distance modulus ($\mu_{\rm obs} = m - M$; Tripp 1998), with M being calculated from the Cepheid host-galaxy distances determined by SHOES (Riess et al. 2022b).

For the CPL model, constraints on the parameter w_a derived from SNe Ia and GRBs + SNe Ia suggest a possible DE evolution ($w_a \neq 0$) within the 1σ confidence region, which is consistent with the results obtained using GRBs alone. However, the statistical measures in Table 1 reveal that the ξIDE model exhibits much higher ΔAIC and ΔBIC values when compared to the ΛCDM and CPL models, indicating that the ΛCDM model is still favored.

The age estimation of old objects at high redshifts is crucial for constraining cosmological parameters (Alcaniz & Lima 1999; Lima & Alcaniz 2000). The quasar APM 08279+5255 at redshift $z = 3.91$ is particularly important in this regard. Its age has been estimated through chemical-evolution studies. Utilizing the Fe/O ratio derived from X-ray observations, Hasinger et al. (2002) provided a rough estimate of $t_{\rm QSO} = 2.0 \sim 3.0$ Gyr. Subsequently, Friaça et al. (2005) used a detailed chemodynamical model to obtain $t_{\rm QSO} = 2.1 \pm 0.3$ Gyr at this redshift. The age of a flat universe at redshift z can be calculated by Alcaniz et al. (2003), Jain & Dev (2006):

$$t(z) = \int_z^{\infty} \frac{dz'}{(1+z')H(z')}. \tag{14}$$

However, the ΛCDM model predicts a cosmic age of 1.63 Gyr at $z = 3.91$ according to the 7 yr WMAP data (Komatsu et al. 2011) ($\Omega_m = 0.272$, $h = 0.704$), while the quasar' s 1σ lower age limit is 1.8 Gyr.

In this work, we use the estimated lower-limit ages of the quasar at $z = 3.91$, with 1σ (1.8 Gyr) and 2σ (1.5 Gyr), to examine the age problem in both the ΛCDM model and the ξIDE model within the parameter space ($\Omega_m - h$ plane) using GRBs + SNe Ia data, as shown in Figure 3. Our calculations indicate that the presence of the quasar APM 08279+5255 is incompatible with the ΛCDM model, which is consistent with the earlier results of Wang & Zhang (2008), Yang & Zhang (2010), and Wang et al. (2010). It can be found that the cosmic age predicted by the ΛCDM model with the best-fit values at $z = 3.91$ (1.38 Gyr) deviates by 2.4σ from the age of the quasar APM 08279+5255 (2.1 Gyr); however, the one predicted by the ξIDE model with the best-fit values at $z = 3.91$ (1.83 Gyr), which can be

Figure 3. The contours correspond to 1σ and 2σ confidence regions in the Ω_m-h plane with GRBs+SNe Ia for the ΛCDM model (left panel) and the ξIDE model (right panel), respectively. The blue, green, and purple curves correspond to the cosmological parameters that would result in a universe age of 2.1 Gyr (the best-fit), 1.8 Gyr (the 1σ limit), and 1.5 Gyr (the 2σ limit) at $z = 3.91$, respectively. The central red dot denotes the best-fit point with GRBs+SNe Ia for the ΛCDM and ξIDE models, respectively.

accommodated the quasar APM 08279+5255 at 0.9σ confidence level. Our calculations show that the ξIDE model can predict significantly higher cosmic ages compared to the ΛCDM model, thereby substantially alleviating the cosmic age problem.

5. Conclusion

In this study, we test the phenomenological interacting scenario (the ξIDE model) with the A118 GRB sample calibrated from the updated OHD measurements in a cosmology-independent approach, Pantheon+ SNe Ia sample, and the age lower limit of quasar APM 08279+5255 at high-z. In the scenario of the ξIDE model, constraints of ξ and w_X derived from GRBs-only, SNe Ia-only, and GRBs+SNe Ia support $\xi + 3w_X < 0$, indicating that energy is transferred from dark energy to dark matter, which is consistent with previous results from Zheng et al. (2022); thus the coincidence problem is alleviated. The best-fit values of H_0 obtained in the ξIDE model deviate by 0.35σ from SH0ES measurements (Riess et al. 2022a) using SNe Ia-only and GRBs+SNe Ia. Considering the age estimate for the quasar APM 08279+5255, our results show that the ξIDE model can accommodate this quasar, predicting significantly higher cosmic ages in comparison to the ΛCDM model and thereby substantially alleviating the cosmic age problem.

The ΛCDM model aligns well with most astronomical observations; however, some recent observations display slight deviations from ΛCDM model (Perivolaropoulos & Skara 2022; Hu & Wang 2023; Carloni et al. 2024; Colgáin et al. 2024a, 2024b, 2024c; Luongo & Muccino 2024). Our analysis also indicates that the constraints for the CPL model with various data sets support the possibility of dark energy evolution ($w_a \neq 0$) within the 1σ confidence region; whereas the ΛCDM model remains favored when comparing ΔAIC and ΔBIC values.

Future work should focus on refining IDE models and exploring their implications with more precise observational data, such as the recent GRBs from Fermi data (Wang & Liang 2024) and BAOs from Dark Energy Spectroscopy Instrument (DESI) data release 1 (DESI Collaboration et al. 2024).

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