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High redshift constraints on dark energy models from the $E_{\rm p,i} - E_{\rm iso}$ correlation in GRBs

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Abstract. Here we test different models of dark energy beyond the standard cosmological constant scenario. We start considering the CPL parameterization of the equation of state (EOS), then we consider a dark energy scalar field (Quintessense). Finally we consider models with dark energy at early times (EDE). Our analysis is based on the Union2 type Ia supernovae data set, a Gamma Ray Bursts (GRBs) Hubble diagram, a set of 28 independent measurements of the Hubble parameter, some baryon acoustic oscillations (BAO) measurements. We performed a statistical analysis and explore the probability distributions of the cosmological parameters for each of the competing models. To build up their own regions of confidence, we maximize some appropriate likelihood functions using the Markov chain Monte Carlo (MCMC) method. Our analysis indicates that the EDE and the scalar field quintessence are slightly favored by the present data. Moreover, the GRBs Hubble diagram alone is able to set the transition region from the decelerated to the accelerated expansion of the Universe in all the tested models. Perspectives for improvements in the field with the THESEUS mission are also described.

Key words. Cosmology: observations, Gamma-ray burst: general, Cosmology: dark energy, Cosmology: distance scale

1. Introduction

Starting at the end of the 1990s, observations of high-redshift supernovae of type Ia (SNIa) revealed the current accelerated expansion of the Universe (see e.g. Perlmutter et al. 1998; Perlmutteret al. 1999; Riess et al. 1998, 2007; Astier et al. 2006; Amanullah et al. 2010), which is driven by the so called dark energy. The so far proposed models of dark energy range from a non-zero cosmological constant (see for instance Carroll 2001), to a potential energy of some not yet discovered scalar field (see for instance Sahniet al. 2003), or effects connected with the inhomogeneous distribution of matter and averaging procedures (see for instance Clarkson & Maartens 2010). In these last two cases the equation of state, EOS, depends on the redshift z. To probe the dynamical evolution of dark energy we consider different competitive cosmological scenarios:

i) an EOS empirically parametrized,
ii) a scalar field model for dark energy,
iii) an early time dark energy model.

In our high-redshift investigation, extended beyond the supernova type Ia (SNIa) Hubble diagram, we use the Union2 SNIa data set, the gamma-ray burst (GRB) Hubble diagram, constructed by calibrating the correlation between the peak photon energy, $E_{\rm p,i}$, and the isotropic equivalent radiated energy, $E_{\rm iso}$ Demianski et al. (2017b). Here we take into account possible redshift evolution effects in the coefficients of this correlation, assuming that they can be modeled through power low terms. We consider also a sample of 28 measurements of the Hubble parameter, compiled in Farroq et al. (2013), Gaussian priors on the distance from the baryon acoustic oscillations (BAO), and the Hubble constant h. Our statistical analysis is based on Monte Carlo Markov Chain (MCMC) simulations to simultaneously compute the full probability density functions (PDFs) of all the parameters of interest.

2. Competitive dark energy models

Here we are looking for some dynamical field that is generating an effective negative pressure. Moreover this could instead be indicating that the Copernican principle cannot be applied at certain scales, and that radial inhomogeneity could mimic the accelerated expansion. Within the Friedman-Lemaitre-Robertson- Walker (FLRW) paradigm, all possibilities can be characterized by the dark energy EOS, $w(z)$. A prior task of observational cosmology is to search for evidence for $w(z) \neq -1$. If we assume that the dark energy evolves, the importance of its equation of state is significant and it determines the Hubble function $H(z)$, and any derivation of it is needed to obtain the observable quantities. Actually it turns out that:

$$H(z,\theta) \;=\; H_0 \sqrt{(1-\Omega_m)g(z,\theta)+\Omega_m(z+1)^3}$$

where $g(z,\theta) = \frac{\rho_{de}(z)}{\rho_{de}(0)} = \exp^{3\int_0^z \frac{w(x,\theta)+1}{x+1}\,dx}$, $w(z,\theta)$ is any dynamical form of the dark energy EOS, and $\theta = (\theta_1, \theta_1 .., \theta_n)$ are the EOS parameters. In the Chevalier-Polarski Linder (CPL) model Chevallier & Polarski (2001); Linder (2003), the dark energy EOS given by

$$w(z) = w_0 + w_1 z(1+z)^{-1}\,, \tag{1}$$

2.1. A scalar field quintessence model

In this section the possible physical realization of dark energy is a cosmic scalar field, φ, minimally coupled to the usual matter action. Here we take into account the specific class of exponential–type potential; in particular we consider an exponential potential for which general exact solutions of the Friedman equations are known Demianski et al. (2011); Piedipalumboet al. (2012). Assuming that φ is minimally coupled to gravity, the cosmological equations are written as

$$H^2 = \frac{8\pi G}{3}(\rho_M + \rho_\varphi)\,, \tag{2}$$

$$\dot{H} + H^2 = -\frac{4\pi G}{3}(\rho_M + \rho_\varphi + 3(p_M + p_\varphi))\,, \tag{3}$$

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0\,. \tag{4}$$

Here

$$\rho_\varphi \equiv \frac{1}{2}\dot{\varphi}^2 + V(\varphi)\,, \quad p_\varphi \equiv \frac{1}{2}\dot{\varphi}^2 - V(\varphi)\,, \tag{5}$$

and

$$w_\varphi \equiv \frac{\dot{\varphi}^2 - 2V(\varphi)}{\dot{\varphi}^2 + 2V(\varphi)}\,. \tag{6}$$

We consider the potential

$$V(\varphi) \propto \exp\left\{-\sqrt{\frac{3}{2}}\varphi\right\}, \quad (7)$$

for which the general exact solution exists (Demianski et al. 2011; Piedipalumboet al. 2012).

2.2. Early dark energy

In this section we consider a model characterized by a non negligible amount of dark energy at early times: these models are connected to the existence of scaling or attractor-like solutions, and they naturally predict a non-vanishing dark energy fraction of the total energy at early stages, Ω_e, which should be substantially smaller than its present value. Following Doran & Robbers (2006); Pettorinoet. al (2013) we use a parametrized representation of the dark energy density fraction, Ω_{DE}, which depends on the present matter fraction, Ω_m, the early dark energy density fraction, Ω_e , and the present dark energy equation of state w_0:

$$\Omega_{DE}(z, \Omega_m, \Omega_e, w_0) = \frac{\Omega_e\left(-\left(1-(z+1)^{3w_0}\right)\right) - \Omega_m + 1}{\Omega_m(z+1)^{-3w_0} - \Omega_m + 1} + \Omega_e\left(1-(z+1)^{3w_0}\right).$$

It turns out that the Hubble function takes the form:

$$H^2(z, \Omega_m, \Omega_e, w_0, \Omega_\gamma, N_{eff}) = \Omega_{DE}(z, \Omega_m, \Omega_e, w_0) + +(z+1)^3\Omega_m + (z+1)^4\Omega_\gamma\left(\frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{eff} + 1\right). \quad (8)$$

Here $N_{eff} = 3$ for three standard model neutrinos that were thermalized in the early Universe and decoupled well before electron-positron annihilation.

3. Observational data

In our approach we use measurements on SNIa and GRB Hubble diagram, distance data from the BAO, and a list of 28 $H(z)$ measurements, compiled in Farroq et al. (2013).

3.1. Supernovae Ia

SNIa observations gave the first strong indication of the recent accelerating expansion of the Universe. First results of the SNIa teams were published by Riess et al. (1998) and Perlmutteret al. (1999). Here we consider the recently updated Supernovae Cosmology Project Union 2.1 compilation Suzukiet al. (2012), which is an update of the original Union compilation and contains 580 SNIa, spanning the redshift range ($0.015 \le z \le 1.4$). We compare the theoretically predicted distance modulus $\mu(z)$ with the observed one through a Bayesian approach, based on the definition of the distance modulus in different cosmological models:

$$\mu(z_j) = 5\log_{10}(D_L(z_j, \{\theta_i\})) + \mu_0, \quad (9)$$

where $D_L(z_j, \{\theta_i\})$ is the Hubble free luminosity distance, and θ_i indicates the set of parameters that appear in different dark energy equations of state considered in our analysis. The parameter μ_0 encodes the Hubble constant and the absolute magnitude M. Given the heterogeneous origin of the Union data set, we used an alternative version of the χ^2:

$$\tilde{\chi}^2_{\rm SN}(\{\theta_i\}) = c_1 - \frac{c_2^2}{c_3}, \quad (10)$$

where

$$c_1 = \sum_{j=1}^{N_{SNIa}} \frac{(\mu(z_j; \mu_0 = 0, \{\theta_i\}) - \mu_{obs}(z_j))^2}{\sigma^2_{\mu,j}}, \quad (11)$$

$$c_2 = \sum_{j=1}^{N_{SNIa}} \frac{(\mu(z_j; \mu_0 = 0, \{\theta_i\}) - \mu_{obs}(z_j))}{\sigma^2_{\mu,j}}, \quad (12)$$

$$c_3 = \sum_{j=1}^{\mathcal{N}_{SNIa}} \frac{1}{\sigma^2_{\mu,j}} \, . \tag{13}$$

It is worth noting that

$$\chi^2_{\rm SN}(\mu_0, \{\theta_i\}) = c_1 - 2c_2\mu_0 + c_3\mu_0^2 \, , \tag{14}$$

which clearly becomes minimum for $\mu_0 = c_2/c_3$, so that $\tilde{\chi}^2_{\rm SN} \equiv \chi^2_{\rm SN}(\mu_0 = c_2/c_3, \{\theta_i\})$.

3.2. Gamma-ray burst Hubble diagram

Gamma-ray bursts are visible up to high redshifts thanks to the enormous energy that they release, and thus may be good candidates for our high-redshift cosmological investigation. We performed our analysis using a new updated GRB Hubble diagram data set obtained by calibrating a 3-d $E_{\rm p,i}$– $E_{\rm iso}$–z relation. Actually, even if recent studies concerning the reliability of the $E_{\rm p,i} - E_{\rm iso}$ relation confirmed the lack, up to now, of any statistically meaningful evidence for a z dependence of the correlation coefficients Demianski et al. (2017a), we include in the calibration terms representing the z-evolution, which are assumed to be power-law functions: $g_{iso}(z) = (1+z)^{k_{iso}}$ and $g_p(z) = (1+z)^{k_p}$ (see for instance Demianski et al. 2017a), so that $E^{'}_{\rm iso} = \dfrac{E_{\rm iso}}{g_{iso}(z)}$ and $E^{'}_{\rm p,i} = \dfrac{E_{\rm p,i}}{g_p(z)}$ are the de-evolved quantities. Therefore we consider a 3D correlation:

$$\log\left[\frac{E_{\rm iso}}{1 \text{ erg}}\right] = b + a \log\left[\frac{E_{\rm p,i}}{300 \text{ keV}}\right] + \\ + \left(k_{iso} - a\, k_p\right) \log{(1+z)} \, . \tag{15}$$

In order to calibrate our de-evolved relation we apply the same local regression technique previously adopted (Demianski et al. 2017a,b), but we consider a 3D Reichart likelihood:

$$L^{3D}_{Reichart}(a, k_{iso}, k_p, b, \sigma_{int}) = \\ \frac{1}{2} \frac{\sum \log{(\sigma^2_{int} + \sigma^2_{y_i} + a^2\sigma^2_{x_i})}}{\log{(1+a^2)}} \\ + \frac{1}{2} \sum \frac{(y_i - a x_i - (k_{iso} - \alpha) z_i - b)^2}{\sigma^2_{int} + \sigma^2_{x_i} + a^2\sigma^2_{x_i}} \, , \tag{16}$$

where $\alpha = a\, k_p$. We also used the MCMC method to maximize the likelihood and ran five parallel chains and the Gelman-Rubin convergence test. We found that $a = 1.87^{+0.08}_{-0.09}$, $k_{iso} = -0.04 \pm 0.1$; $\alpha = 0.02 \pm 0.2$; $\sigma_{int} = 0.35^{+0.02}_{-0.03}$, so that $b = 52.8^{+0.03}_{-0.06}$. After fitting the correlation and estimating its parameters, we used them to construct the GRB Hubble diagram.

3.3. Baryon acoustic oscillations data

Baryon acoustic oscillations data are promising standard rulers to investigate different cosmological scenarios and models. They are related to density fluctuations induced by acoustic waves that are created by primordial perturbations. To use BAOs as a cosmological tool, we define:

$$d_z = \frac{r_s(z_d)}{d_V(z)} \, , \tag{17}$$

where z_d is the drag redshift, $r_s(z)$ is the comoving sound horizon,

$$r_s(z) = \frac{c}{\sqrt{3}} \int_0^{(1+z)^{-1}} \frac{da}{a^2 H(a) \sqrt{1 + (3/4)\Omega_b/\Omega_\gamma}} \tag{18}$$

and $d_V(z)$ the volume distance. Moreover, BAO measurements in spectroscopic surveys allow to directly estimate the expansion rate H(z), converted into the quantity $D_H(z) = \dfrac{c}{H(z)}$, and put constraints on the comoving angular diameter distance $D_M(z)$. The BAO data used in our analysis are summarized in Table 1 and are taken from Aubourg et al. (2015). Here, the BAO scale r_d is the radius of the sound horizon at the decoupling era.

3.4. H(z) measurements

The measurements of Hubble parameters are a complementary probe to constrain the cosmological parameters and investigate the dark

Table 1. BAO data used in our analysis.

Redshift	D_V/r_d	D_M/r_d	D_H/r_d
0.106	3.047 ± 0.137	–	–
0.15	4.480 ± 0.168	–	–
0.32	8.467 ± 0.167	–	–
0.57	–	14.945 ± 0.210	20.75 ± 0.73
2.34	–	37.675 ± 2.171	9.18 ± 0.28
2.36	–	36.288 ± 1.344	9.00 ± 0.30
2.34	–	36.489 ± 1.152	9.145 ± 0.204

energy Farroq et al. (2013). The Hubble parameter depends on the differential age of the Universe as a function of redshift and can be measured using the so-called cosmic chronometers. dz is obtained from spectroscopic surveys with high accuracy, and the differential evolution of the age of the Universe dt in the redshift interval dz can be measured provided that optimal probes of the aging of the Universe, that is, the cosmic chronometers, are identified. The most reliable cosmic chronometers at present are old early-type galaxies that evolve passively on a timescale much longer than their age difference, which formed the vast majority of their stars rapidly and early and have not experienced subsequent major episodes of star formation or merging. Moreover, the Hubble parameter can also be obtained from the BAO measurements. We used a list of 28 $H(z)$ measurements, compiled in Farroq et al. (2013).

4. Statistical analysis

To test the cosmological parameters described above, we use a Bayesian approach based on MCMC method. In order to set the starting points for our chains, we first performed a preliminary and standard fitting procedure to maximize the likelihood function $\mathcal{L}(\mathbf{p})$:

$$\mathcal{L}(\mathbf{p}) \propto \frac{\exp(-\chi^2_{SNIa/GRB}/2)}{(2\pi)^{\frac{N_{SNIa/GRB}}{2}}|\mathbf{C}_{SNIa/GRB}|^{1/2}} \times \frac{\exp(-\chi^2_{BAO}/2)}{(2\pi)^{N_{BAO}/2}|\mathbf{C}_{BAO}|^{1/2}} \times$$

$$\times \frac{1}{\sqrt{2\pi\sigma^2_{\omega_m}}} \exp\left[-\frac{1}{2}\left(\frac{\omega_m - \omega_m^{obs}}{\sigma_{\omega_m}}\right)^2\right] \quad (19)$$

$$\times \frac{1}{\sqrt{2\pi\sigma^2_h}} \exp\left[-\frac{1}{2}\left(\frac{h - h_{obs}}{\sigma_h}\right)^2\right]$$

$$\frac{\exp(-\chi^2_H/2)}{(2\pi)^{N_H/2}|\mathbf{C}_H|^{1/2}}$$

$$\times \frac{1}{\sqrt{2\pi\sigma^2_{\mathcal{R}}}} \exp\left[-\frac{1}{2}\left(\frac{\mathcal{R} - \mathcal{R}_{obs}}{\sigma_{\mathcal{R}}}\right)^2\right].$$

Here

$$\chi^2(\mathbf{p}) = \sum_{i,j=1}^{N} \left(x_i - x_i^{th}(\mathbf{p})\right) C_{ij}^{-1} \left(x_j - x_j^{th}(\mathbf{p})\right) \quad (20)$$

$\mathbf{p}$ is the set of parameters, N is the number of data points, x_i is the $i-th$ measurement; $x_i^{th}(\mathbf{p})$ indicate the theoretical predictions for these measurements and depend on the parameters $\mathbf{p}$. C_{ij} is the covariance matrix (specifically, $\mathbf{C}_{SNIa/GRB/H}$ indicates the SNIa/GRBs/H covariance matrix); $(h^{obs}, \sigma_h) = (0.742, 0.036)$ (Riess et al. 2009), and $(\omega_m^{obs}, \sigma_{\omega_m}) = (0.1356, 0.0034)$ (Planck Collaboration 2016). It is worth noting that the effect of our prior on h is not critical at all so that we are certain that our results are not biased by this choice. The term

$\dfrac{1}{\sqrt{2\pi\sigma_{\mathcal{R}}^2}}\exp\left[-\dfrac{1}{2}\left(\dfrac{\mathcal{R}-\mathcal{R}_{obs}}{\sigma_{\mathcal{R}}}\right)^2\right]$ in the likelihood (20) considers the shift parameter $\mathcal{R}$:

$$\mathcal{R} = H_0\sqrt{\Omega_M}\int_0^{z_\star}\frac{dz'}{H(z')}\,, \tag{21}$$

where $z_\star = 1090.10$ is the redshift of the surface of last scattering (Bond et al. 1997; Efstathiou et al. 1999). According to the Planck data $(\mathcal{R}_{obs}, \sigma_{\mathcal{R}}) = (1.7407, 0.0094)$.

Finally, the term $\dfrac{\exp(-\chi^2_H/2)}{(2\pi)^{\mathcal{N}_H/2}|\mathbf{C}_H|^{1/2}}$ in Eq. (20) is the likelihood relative to the measurements of $H(z)$. For each cosmological model we sample its space of parameters, by running five parallel chains and use the Gelman - Rubin diagnostic approach to test the convergence. In Tables 2, 3, and 4 we present the results of our analysis.

5. Prospectives with THESEUS

So far we showed that the $E_{\rm p,i}-E_{\rm iso}$ correlation has significant implications for the use of GRBs in cosmology and therefore GRBs are powerful cosmological probe, complementary to other probes. Future GRB missions, like, e.g., the proposed THESEUS observatory (Amati et al. 2018), will increase substantially the number of GRB usable to construct the $E_{\rm p,i}-E_{\rm iso}$ correlation up to redshift $z \simeq 10$ and will allow a better calibration of the correlation. Here, we compare the confidence intervals on the cosmological parameters for a FLRW flat model, for the CPL parametrization of the dark energy EOS, obtained with the real sample of our 162 GRBs and a simulated sample of 772 objects. The simulated data set was obtained by taking into account the distribution of the observed $E_{\rm p,i}-E_{\rm iso}$ correlation, the distribution of the uncertainties in the measured values of$E_{\rm p,i}$ and $E_{\rm iso}$, and the observed redshift distribution of GRBs. In order to build up our simulated GRB Hubble diagram data set, we first calibrate our 3-d $E_{\rm p,i}$– $E_{\rm iso}$–z relation. Therefore we start the cosmological investigations, considering only the CPL model. In Table 4 are summarized the results of our analysis: with our mock sample of GRBs the accuracy in measuring Ω_m and the dark energy EOS will be comparable to that currently provided by SNe data.

6. Discussion and conclusions

The $E_{\rm p,i}-E_{\rm iso}$ correlation has significant implications for the use of GRBs in cosmology. Here we explored a 3D Amati relation in a way independent of the cosmological model, and taking into account a possible redshift evolution effects of its correlation coefficients (Demianski et al. 2017a) parametrized as power low terms: $g_{iso}(z) = (1+z)^{k_{iso}}$ and $g_p(z) = (1+z)^{k_p}$. Low values of k_{iso} and k_p would indicate negligible evolutionary effects. Using the recently updated data set of 162 high-redshift GRBs, we applied a local regression technique to estimate the distance modulus using the recent Union SNIa sample (Union2.1). The derived calibration parameters are statistically fully consistent with the results of our previous work (Demianski et al. 2011, 2017a), and confirm that the correlation shows, at this stage, only weak indication of evolution. The fitted calibration parameters have been used to construct a calibrated GRB Hubble diagram, which we adopted as a tool to constrain different cosmological models: we considered the CPL parameterization of the EOS, an exponential dark energy scalar field, and, finally a model with dark energy at early times. To compare these models we assumed that the CPL is true and checked the occurrence of $\chi^2_{EDE/Quintessence} < \chi^2_{CPL}$, varying the parameters specific of the EDE and scalar field model respectively. It turns out that the EDE and the scalar field quintessence are slightly favored by the present data. Moreover, it is worth noting that, also without the SNIa, the GRBs Hubble diagram is able to set the transition region from the decelerated to the accelerated expansion in all the tested cosmological models. This definitively proves that GRBs are powerful cosmological probe, complementary to other probes. Future GRBs missions (THESEUS) will increase the number of GRB usable to construct

Table 2. Constraints on the EOS parameters for the CPL model.

CPL Parametrization								
Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
	Full dataset				No SNIa			
Ω_m	0.23	0.24	(0.19, 0.27)	(0.14, 0.29)	0.19	0.2	(0.16, 0.22)	(0.10, 0.27)
Ω_b	0.046	0.046	(0.04, 0.047)	(0.043, 0.049)	0.055	0.054	(0.045, 0.068)	(0.037, 0.06)
w_0	-0.88	-0.87	(-1.0, -0.74)	(-1.18, -0.67)	-0.7	-0.7	(-0.8, -0.62)	(-1.05, -0.6)
w_a	0.16	0.17	(-0.15, 0.43)	(-0.3, 0.49)	0.39	0.42	(0.3,0.48)	(0.1, 0.52)
h	0.69	0.69	(0.68, 0.71)	(0.67, 0.72)	0.67	0.67	(0.64, 0.69)	(0.64, 0.72)

Table 3. Constraints on the parameters for the scalar field quintessence model.

Scalar field Quintessence								
Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
	Full dataset				No SNIa			
Ω_b	0.051	0.051	(0.050, 0.051)	(0.049, 0.052)	0.051	0.051	(0.050, 0.0514)	(0.049,0.052)
H_0	0.98	0.98	(0.95,0.99)	(0.94, 1.01)	0.96	0.96	(0.94, 0.98)	(0.92, 1.05)
h	0.69	0.68	(0.67,0.695)	(0.67, 0.7)	0.67	0.67	(0.65, 0.68)	(0.64, 0.70)

Table 4. Constraints on the parameters for the EDE model.

Early Dark Energy								
Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
	Full dataset				No SNIa			
Ω_m	0.29	0.29	(0.27, 0.31)	(0.25, 0.33)	0.285	0.285	(0.271, 0.298)	(0.258, 0.312)
Ω_b	0.047	0.048	(0.040 0.05)	(0.037, 0.052)	0.045	0.048	(0.035, 0.047)	(0.032, 0.054)
w_0	-0.66	-0.67	(-0.85, -0.56)	(-1.33, -0.5)	-0.65	-0.63	(-0.75, -0.53)	(-0.85,-0.50)
Ω_e	0.04	0.035	(0.032, 0.043)	(0.026, 0.05)	0.025	0.023	(0.009, 0.039)	(0.023, 0.03)
h	0.71	0.71	(0.69, 0.71)	(0.69, 0.72)	0.71	0.71	(0.67,0.73)	(0.67, 0.75)

Table 5. Constraints on the EOS parameters for the CPL model from the simulated dataset.

CPL Parametrization								
Id	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL	$\langle x \rangle$	$\tilde{x}$	68% CL	95% CL
	Full dataset				No SNIa			
Ω_m	0.19	0.19	(0.16, 0.23)	(0.14, 0.26)	0.17	0.17	(0.16, 0.2)	(0.11, 0.23)
Ω_b	0.046	0.046	(0.04, 0.047)	(0.043, 0.049)	0.055	0.054	(0.045, 0.068)	(0.037, 0.06)
w_0	-0.8	-0.78	(-0.93, -0.69)	(-1.04, -0.63)	-0.7	-0.7	(-0.75, -0.63)	(-0.81, -0.6)
w_a	0.32	0.34	(0.19, 0.44)	(0.05, 0.5)	0.38	0.39	(0.3,0.47)	(0.12, 0.49)
h	0.66	0.69	(0.68, 0.70)	(0.67, 0.71)	0.67	0.67	(0.64, 0.68)	(0.62, 0.72)

the $E_{\rm p,i} - E_{\rm iso}$ correlation up to redshift $z \simeq 10$ and will allow a better calibration of the correlation. Probably also a self-calibration will be available. Therefore, the effective role of z evolution will be clarified, and the GRBs Hubble diagram will be able to measure the cosmological parameters and to test the evolution of dark energy, in a complementary way to type

Ia SNe. Indeed, we used a simulated dataset of 772 GRBs to constraint the cosmological parameters for a FLRW flat model, in the case of the CPL parametrization of the dark energy EOS: it turns out that the accuracy in measuring Ω_m, h, and the dark energy EOS, will be competitive with respect to that currently provided by SNe data.

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