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Constraints on Cosmological Parameters Using Gamma-Ray Bursts with Measured and Machine Learning–Derived Redshifts

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Gamma-Ray Bursts (GRBs), the most luminous explosions in the cosmos, are promising tools for cosmology due to their potential as standardizable candles. Among the empirical correlations proposed for this purpose, the Yonetoku relation, which connects the intrinsic peak energy ($E_{\rm i,p}$) of the νF_ν spectrum to the isotropic peak luminosity ($L_{\rm iso}$), provides a mean to probe distances beyond the range of Type Ia supernovae (SNe Ia). In this work, the Yonetoku relation is calibrated and analyzed using GRBs with measured redshifts and a large sample of GRBs with pseudo-redshifts obtained using Machine Learning (ML). This analysis focuses on estimating the distance modulus and constraining parameters of a flat ΛCDM cosmology using this relation. A joint Markov Chain Monte Carlo analysis is applied to simultaneously determine the Yonetoku relation parameters (k, m) and cosmological parameters (H_0, Ω_Λ). This method is applied across the full redshift range of the GRB samples. This unified fitting strategy avoids the circularity problem in GRB cosmology, in which adopting fixed cosmological model parameters for calibrating the correlation parameters can bias subsequent cosmology parameter inference. A total of 116 *Fermi*-GBM GRBs with known redshifts are utilized in combination with the pseudo-redshift sample of 1576 GRBs. In addition, a combination with SNe Ia datasets from Union 2.1, the Dark Energy Survey (DES), and Pantheon+SHOES is employed. This combined approach yields a consistent value for H_0 and Ω_Λ, indicating that GRBs with well-modeled pseudo-redshifts can serve as effective high-redshift cosmological probes.

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1. Introduction

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe, first detected in 1967 [1] and later confirmed as extragalactic by BATSE observations [2]. They are generally classified as short GRBs (SGRBs), originating from compact object mergers, and long GRBs (LGRBs), associated with massive star collapses, with the dividing line at $T_{90} \sim 2$–4 s, depending on the instrument [3, 4]. GRBs release $\gtrsim 10^{51}$ ergs in γ rays and are observed across a broad energy range (8 keV – >300 GeV) by instruments including *Fermi*-GBM/LAT, *Swift*-BAT, and Konus-*Wind* [5–8]. Their spectra often exhibit multiple components, modeled by the Band function with occasional blackbody or high-energy power-law contributions [9–12].

GRBs have been detected at redshifts up to $z \sim 9.4$ [13], making them valuable cosmological probes beyond the reach of Type Ia supernovae (SNe Ia), as γ-ray emission is minimally affected by dust [14]. Empirical correlations, such as the Amati relation ($E_{\rm i,p}$–$E_{\rm iso}$) [15, 16] and Yonetoku relation ($E_{\rm i,p}$–$L_{\rm iso}$) [17], link intrinsic spectral properties (peak of the νF_ν spectrum $E_{\rm i,p}$) to energetics (isotropic-equivalent γ-ray energy $E_{\rm iso}$ or peak luminosity $L_{\rm iso}$). These relations offer the potential to standardize GRBs as cosmological candles, although the circularity problem, where redshift estimation depends on assumed cosmology, remains a challenge [18, 19].

To address this, machine learning (ML) and deep learning methods have been employed to infer pseudo-redshifts directly from observed GRB properties without assuming a cosmological model. Techniques including recurrent neural networks, Bayesian neural networks, and ensemble learners have successfully predicted redshifts for hundreds of LGRBs [20–25]. These expanded samples enable self-consistent tests of the Amati and Yonetoku correlations, providing a pathway to standardize GRBs as independent cosmological probes. In this work, we present a unified analysis that simultaneously calibrates the Yonetoku relation and constrains cosmological parameters using GRBs with both true and pseudo-redshifts. This approach, unlike previous studies and our earlier work [24], performs a joint inference of GRB correlation and cosmological parameters within a single likelihood, incorporating additional constraints from multiple SNe Ia samples.

2. Methods and Analysis

The Yonetoku relation [17] is expressed as

$$L_{\rm iso} = k \left(\frac{E_{\rm i,p}}{E_0}\right)^m , \tag{1}$$

where $E_{\rm i,p} = E_{\rm pk}(1+z)$, with $E_{\rm pk}$ being the peak energy of the νF_ν spectrum of the highest γ-ray flux within one-second interval, and $E_0 = 100$ keV is a reference energy. Correspondingly, $L_{\rm iso}$ is the isotropic-equivalent peak γ-ray luminosity calculated from the peak bolometric flux $P_{\rm bol}$ using the same spectrum as

$$L_{\rm iso} = 4\pi d_{\rm L}^2 P_{\rm bol} . \tag{2}$$

Here $d_{\rm L}$ is the luminosity distance. An observational estimate of it can be obtained from equations (1) and (2) as

$$d_{\rm L} = \sqrt{\frac{k}{4\pi P_{\rm bol}} \left(\frac{E_{\rm i,p}}{E_0}\right)^m} . \tag{3}$$

Cosmological parameters such as Hubble constant H_0 and dark energy density Ω_Λ can be constrained by comparing equation (3) with theoretical model

$$d_\mathrm{L} = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{(1-\Omega_\Lambda)(1+z')^3+\Omega_\Lambda}}, \tag{4}$$

for a flat ΛCDM cosmology.

In this analysis, the distance modulus for each GRB with known and/or pseudo-redshift is calculated as

$$\mu(z) = 5\log_{10}\left(\frac{d_\mathrm{L}}{1\,\mathrm{Mpc}}\right) + 25. \tag{5}$$

both for observational and theoretical values of d_L. Uncertainty for observational values is obtained through standard error propagation as

$$\sigma_{\mu(z)} = \frac{5}{2\ln 10}\left[\left(\frac{\sigma_{P_\mathrm{bol}}}{P_\mathrm{bol}}\right)^2 + \left(\frac{m\,\sigma_{E_\mathrm{i,p}}}{E_\mathrm{i,p}}\right)^2\right]^{1/2}. \tag{6}$$

The cosmological parameters and the Yonetoku relation parameters are simultaneously fitted using Markov Chain Monte Carlo (MCMC) analysis through a chi-square minimization, including priors on the parameters k and m as

$$\chi^2(H_0,\Omega_\Lambda,k,m) = \sum_{i=1}^{N}\left[\frac{\mu^\mathrm{ex}(z_i,k,m) - \mu^\mathrm{th}(z_i;H_0,\Omega_\Lambda)}{\sigma_{\mu(z_i)}}\right]^2 + \sum_j\left(\frac{\theta_j-\bar{\theta}_j}{\sigma_{\theta_j}}\right)^2 \tag{7}$$

Here θ_j are Gaussian priors for the parameters with mean values $\bar{\theta}_j$ and standard deviations σ_{θ_j}. ($\bar{k} = 0.5$, $\bar{m} = 1.35$) are mean values of the priors, and ($\sigma_k = 0.07$, $\sigma_m = 0.18$) are their corresponding standard deviations, derived from the GBM-GRB data fit. For the GRB-only analysis, additional priors on cosmological parameters ($\bar{H}_0 = 73.04, \sigma_{H_0} = 1.04; \bar{\Omega}_\Lambda = 0.70, \sigma_{\Omega_\Lambda} = 0.02$) were also used following Ref. [30]. For a combined fit to the GRB and SNe Ia data $\chi^2_\mathrm{GRB}(H_0,\Omega_\Lambda,k,m) + \chi^2_\mathrm{SNe}(H_0,\Omega_\Lambda)$ was minimized, where μ^ex and σ_μ for the SNe Ia data are used from publicly available sources as discussed below.

2.1 Data Sample

The data sample used in this work is based on previous results reported in Ref. [24], where machine-learning techniques were applied to estimate redshifts for LGRBs in the Fermi-GBM catalog. In that study, a supervised regression framework was developed using a set of prompt-emission observables, including spectral peak energy, photon indices, fluence, and peak flux, as input features. Several models were trained and evaluated (deep neural networks, random forests), and the final pseudo-redshift catalog was produced using the best-performing ensemble model selected through coefficient, mean absolute error, and statistical tests (p-value).

The resulting pseudo-redshift table is publicly available on Zenodo[1]. From this catalog, we selected a sample of 1576 LGRBs with predicted redshifts for use in the joint calibration and cosmological analysis presented in this work.

[1] https://doi.org/10.5281/zenodo.13695954

Additionally, 116 LGRBs with observationally measured redshifts, 580 SNe Ia from the U2.1 sample [26], 329 SNe Ia from the Dark Energy Survey (DES[2] [27]), and 1550 SNe Ia (1701 data entries) from the Pantheon+ Supernova and H_0 for the Equation of State of dark Energy project (SHOES[3] [28]) have been used in this analysis.

3. Results

Figure 1 shows the MCMC corner plots, generated by using the `emcee` sampler [29], displaying the posterior distributions and uncertainties of the parameters obtained from the simultaneous fit of H_0, Ω_Λ, k, and m for the GRB-only data with true-redshift and pseudo-redshift from Ref. [24]. The best-fit parameter values are also listed in Table 1. A Hubble diagram with the distance modulus using best-fit H_0 and Ω_Λ is shown (red-dashed curve) in figure 2 along with $\mu(z)$ values for GRBs with true-redshift (red circles) and pseudo-redshift (gray circles).

Figure 2 shows the posterior distributions and uncertainties of the parameters as in figure 1, but here GRB data are combined with the SNe Ia data from the U2.1 [26], DES [27], and Pantheon+ [28]. The distance modulus using the combined GRB and SNe Ia best-fit cosmological parameters is shown in figure 3 as the black-solid curve. The $\mu(z)$ values for SNe Ia data points are also shown in the same figure. Best-fit parameters are also listed in Table 1. Results of combining different SNe Ia dataset(s) with GRBs (true and pseudo redshifts), to investigate potential systematic differences in the inferred values of H_0 and Ω_Λ, are also listed in Table 1.

Table 1: Best-fit cosmological and Yonetoku relation parameters from the GRB data alone (True+Pseudo redshift) and from the combination with different SNe Ia data. Results from the highlighted cases are shown in figures. Also listed are best-fit parameters obtained in other studies.

Dataset	H_0	Ω_Λ	k	m
This Study				
GRBs-only	73.05 ± 1.06	0.67 ± 0.02	0.93 ± 0.04	1.03 ± 0.07
GRBs + SNe (U2.1 only)	68.97 ± 0.43	0.65 ± 0.03	0.97 ± 0.04	1.00 ± 0.08
GRBs + SNe (DES only)	69.86 ± 0.28	0.54 ± 0.02	0.89 ± 0.04	1.00 ± 0.08
GRBs + SNe (Pantheon+ only)	72.62 ± 0.25	0.62 ± 0.02	0.90 ± 0.04	1.00 ± 0.08
GRBs + SNe (U2.1+DES)	70.06 ± 0.24	0.63 ± 0.02	0.94 ± 0.04	1.00 ± 0.08
GRBs + SNe (U2.1, Pantheon+)	72.25 ± 0.22	0.67 ± 0.02	0.94 ± 0.04	1.00 ± 0.08
GRBs + SNe (All)	71.46 ± 0.17	0.64 ± 0.01	0.92 ± 0.04	1.03 ± 0.07
Previous Studies				
GRB+W2016 + SNe [12]	70.0 ± 0.5	0.72 ± 0.03	1.34 ± 0.07	1.18 ± 0.18
Cepheids + SNe [30]	73.04 ± 1.04	0.70 ± 0.02	–	–
Pantheon+ SNe [32]	73.5 ± 1.1	0.67 ± 0.02	–	–
CMB [31]	67.4 ± 0.5	0.68 ± 0.01	–	–

4. Discussion and Conclusions

In these analyses, the Yonetoku relation parameters (k, m) and cosmological parameters (H_0, Ω_Λ) have been fitted simultaneously to avoid the so-called circularity problem of using certain

[2] https://www.darkenergysurvey.org/the-des-project/data-access/
[3] https://github.com/PantheonPlusSHOES/DataRelease

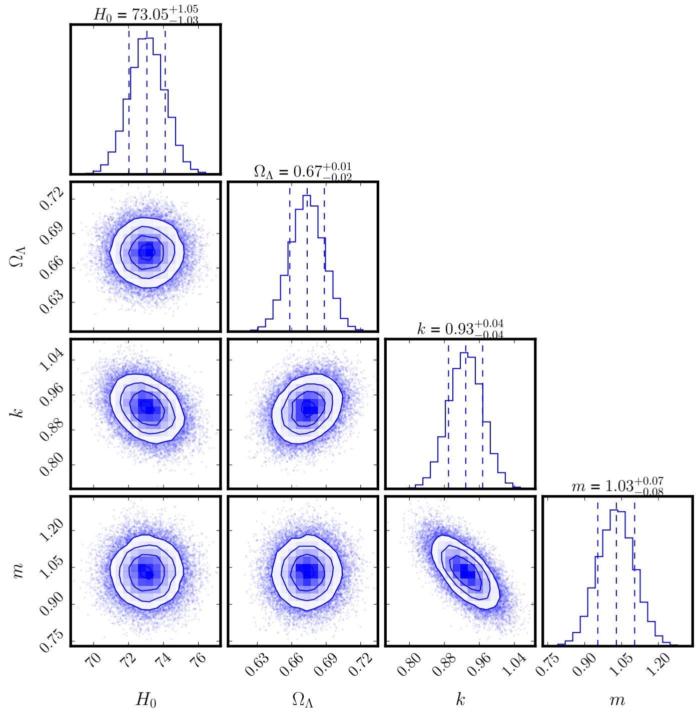

Figure 1: Estimated cosmological parameters (H_0, Ω_Λ) and Yonetoku relation parameters (k, m) from the MCMC analysis when combining pseudo-redshift GRBs (GBM data) with true-redshift GRBs.

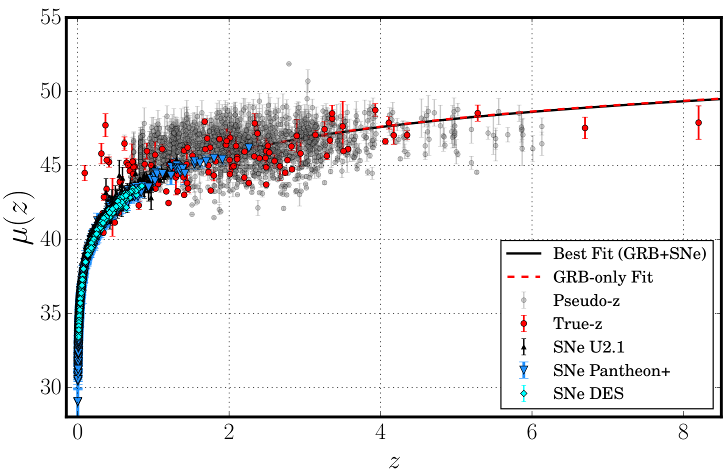

Figure 2: Distance modulus vs. redshift for GRBs and SNe Ia. The red-dashed curve corresponds to the best-fit cosmological and Yonetoku relation parameters obtained for the GRB data only. The black-solid curve corresponds to the same, but for the GRB data combined with all SNe Ia data.

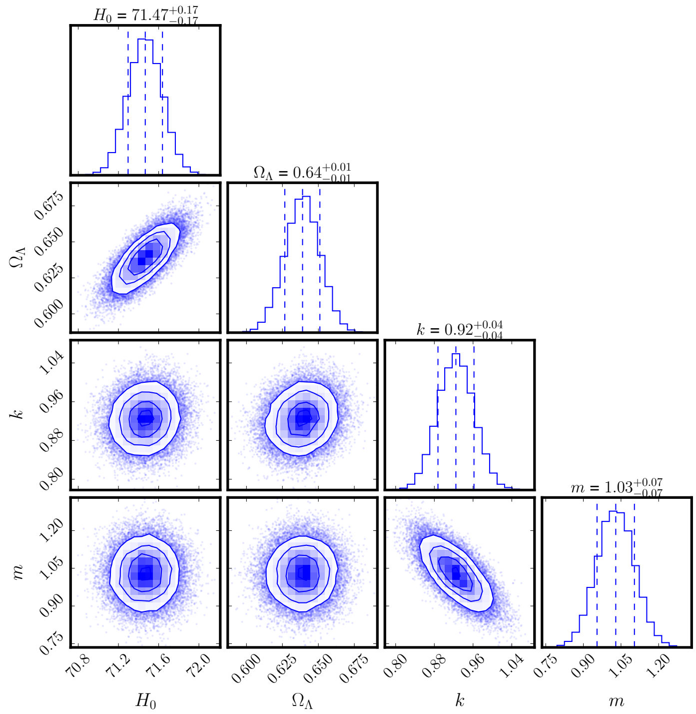

Figure 3: Estimated cosmological parameters (H_0, Ω_Λ) and Yonetoku relation parameters (k, m) from the MCMC analysis, combining pseudo-redshift GRBs (GBM data) with true-redshift GRBs as well as SNe Ia data (U2.1 + DES + Pantheon+).

values for H_0 and Ω_Λ to obtain k and m, and then use best-fit k and m values to constrain H_0 and Ω_Λ. Key findings from these analyses are the following:

- **GRBs-only analysis:** Using GRBs alone provides limited constraints on cosmological parameters. This limitation arises primarily from the small number of low-redshift GRBs and the degeneracy between H_0 and the intercept parameter k of the Yonetoku relation. To improve the fits, priors on both cosmological (H_0, Ω_Λ) and correlation (k, m) parameters were applied, resulting in better parameter estimates, as illustrated in Figure 1. A broader range of H_0 prior increases uncertainties but leaves central values largely unchanged.

- **GRBs combined with SNe Ia:** Since GRBs alone cannot tightly constrain cosmological parameters without putting priors on them, combining GRBs with various SNe Ia samples (without imposing cosmological priors) provides a more robust determination of H_0 and Ω_Λ. This combination effectively breaks the degeneracy and enhances the precision of the cosmological fits, as shown in Figure 3.

- **Distance modulus:** Figure 2 presents the distance modulus relation (μ vs. z). All the best-fit parameter values to the GRB-only data and to the GRB + SNe (All) data are within $\pm 1\,\sigma$ errors (see Table 1, highlighted rows). A change in the priors on H_0 and Ω_Λ in the GRB-only analysis do not change these results substantially. Therefore, GRBs hold promise as standardizable cosmological candles. Constraints from different other SNe Ia compilations together with GRBs and their corresponding best-fit values provided in Table 1 indicate that H_0 values are compatible in all cases, while Ω_Λ values vary.

- **Comparison with previous studies:** GRB + SNe (All) analysis presented here and an analysis using GRBs with true-z and U2.1 SNe in Ref. [12] give compatible H_0 but significantly different Ω_Λ values. When compared to the Cepheid + SNe [30] or Pantheon+ SNe [32] results, both H_0 and Ω_Λ values are compatible with the GRB-only analysis presented here within $\pm 1\,\sigma$ errors. When compared to CMB results [31] H_0 from the GRB-only analysis is in tension just like the Cepheid + SNe [30] or Pantheon+ SNe [32] results. However, GRB + SNe (All) analysis results reduce the tension and give an H_0 value intermediate between the early- and late-universe measurements.

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