Gamma-ray bursts and dark energy–dark matter interaction

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ABSTRACT

In this work, gamma-ray burst (GRB) data are used to place constraints on a putative coupling between dark energy and dark matter. Type Ia supernovae constraints from the Sloan Digital Sky Survey II (SDSS-II) first-year results, the cosmic microwave background radiation background shift parameter from Wilkinson Microwave Anisotropy Probe seven year results and the baryon acoustic oscillation peak from the SDSS are also discussed. The prospects for the field are assessed, as more GRB events become available.

Key words: gamma-ray burst: general – cosmological parameters – dark energy – dark matter.

1 INTRODUCTION

The nature of dark energy and dark matter remains an outstanding open problem in cosmology. In spite of the success of the Λ cold dark matter (ΛCDM) parametrization, one must consider more complex models in order to cast some light on the substance of the dark components of the Universe. In this work, one considers models with interacting dark energy and dark matter components. There are several useful tools to probe the phenomenology of these models, such as cosmic microwave background radiation (CMBR) data (Komatsu et al. 2010), baryon acoustic oscillation (BAO) (Moldenhauer & Ishak 2009; Reid et al. 2010), Supernovae (SNe) data (Kessler et al. 2009) and the deviation from the virial equilibrium of galaxy clusters (Bertolami, Gil Pedro & Le Delliou 2007, 2009; Abdalla 2009). It has been suggested (Schaefer 2003; Bertolami & Tavares 2006) that gamma-ray burst (GRB) may be used to extend the Hubble diagram to high redshifts, greater than z = 5. At these epochs the Universe was dominated by dark matter, from which follows that this tool is less sensitive to dark energy. However, for models where dark energy and matter are coupled (Amendola et al. 2003; Bertolami et al. 2007) or unified (Kamenshcik, Moschella & Pasquier 2001; Bento, Bertolami & Sen 2002, 2003; Barreiro, Bertolami & Torres 2008), GRBs might be a particularly useful tool (Bertolami & Tavares 2006).

In the late 1960s, the Vela array of military satellites detected flashes of radiation originating in apparently random directions in space. The observed bursts lasted between tens of millisecond and thousands of seconds, and were composed of soft (0.01 to 1 MeV) gamma-rays. Subsequently space missions such as the US Apollo programme and the Soviet Venera probes confirmed the existence of the GRBs, even though its rate of occurrence was virtually unknown until the deployment of the Compton Gamma-Ray Observatory, in 1991. This observatory was equipped with a sensitive gamma-ray detector, the Burst and Transient Source Explorer (BATSE) instrument which was able to detect one or two events per day. The collected data allowed to divide GRBs into two categories: short duration bursts (short bursts) and long duration bursts (long bursts). The former usually last for less than two seconds and are dominated by high-energy photons; the latter last longer than two seconds and are dominated by lower energy photons. However, this distinction is not always clear.

The physical origin of GRBs has been debated for a long time, before their exact position and a reliable estimate of their distance was lacking (see e.g. Bertolami 1999 and references therein). In 1997, several GRBs were detected by the BeppoSAX satellite. A GRB prompt emission is followed by an afterglow emission composed by all wavelengths. Depending on its brightness, an afterglow can last from days to months after the burst itself, the transient phase. The detection of the afterglow did manifold the information on GRBs. Through their afterglow, GRB’s X-ray, optical and radio counterparts were observed, as well as their redshifts (Fan & Piran 2008), confirming the cosmological origin of most, if not all, GRBs. When, in 2003, the long GRB 030329 was discovered and linked with the supernova SN2003dh (Cobb et al. 2004), it became clear that GRBs are linked with the release of gravitational energy during the collapse of stellar mass objects. GRBs are most likely collimated, considering they reach integrated luminosities up to L ∼ 10^{53} erg s^{-1}, making it hard to associate them with an astrophysical object otherwise. This high energy release creates an outflow that expands relativistically. Two forms of shocks are ensued by the burst, the forward shock and the reverse one, which one separated by a contact discontinuity (Lyutikov 2009). If the ejected plasma
The analysis assumes for the ratio of the dark components that (Bertolami et al. 2007)
\[
\frac{\rho_{\text{DE}}}{\rho_{\text{DM}}} = \frac{\Omega_{\text{DE}0}}{\Omega_{\text{DM}0}} = \frac{3}{2}\left(1 + \frac{1}{z}\right)^{-\eta}
\]
for a constant \(\eta\), where \(a\) is the scalefactor, assumed that at present \(a_0 = 1\), and \(z\) is the redshift.

Inserting the time derivative of equation (3) into equations (1) and (2), one obtains for the coupling
\[
\zeta = \frac{\xi_0}{\Omega_{\text{DEi}} + \Omega_{\text{DMi}}(1 + z)^{-\eta}}
\]
where \(\zeta_0 = -(\eta + 3w)\Omega_{\text{DEi}}\). Note that when \(\eta = -3w\), there is no interaction between dark energy and dark matter, since \(\zeta = 0\).

The solutions for equations (1) and (2) can be written as
\[
\rho_{\text{DM}} = (1 + z)^3\rho_{\text{DMi}}\left[\frac{\Omega_{\text{DEi}}(1 + z)^{-\eta} + \Omega_{\text{DMi}}}{\Omega_{\text{DEi}} + \Omega_{\text{DMi}}}\right]^{(-\eta-3w)/\eta}
\]
\[
\rho_{\text{DE}} = (1 + z)^{\eta+3}\rho_{\text{DEi}}\left[\frac{\Omega_{\text{DEi}}(1 + z)^{-\eta} + \Omega_{\text{DMi}}}{\Omega_{\text{DEi}} + \Omega_{\text{DMi}}}\right]^{(-\eta-3w)/\eta}.
\]

Inserting equations (3), (5) and (6) into the Friedmann equation for a flat universe, \(H^2 = H_0^2(\rho_{\text{DM}} + \rho_{\text{DE}} + \rho_\gamma)/\rho_0\), where \(H_0\) and \(\rho_0\) are the Hubble constant and the total energy density at present, one obtains
\[
E^2(z) = (1 + z)^3\left[\frac{\Omega_{\text{DM0}} + \Omega_{\text{DMi}}(1 + z)^{-\eta}h^{(-3w)/\eta}}{\Omega_{\text{DM0}} + \Omega_{\text{DMi}}h^{(-3w)/\eta} + \Omega_{\text{DE0}}} + \Omega_{\text{DE0}}\right]
\]
where \(\Omega_{\text{DM0}}\) and \(\Omega_{\text{DE0}}\) are the baryon and DM energy densities at present and \(E(z) = H(z)/H_0\).

It is interesting to point out that the Generalized Chaplygin Gas model (GGG) (Kamenshchik et al. 2001; Bento et al. 2002), an unified model of dark energy and dark matter, can be seen as a particular case of this interacting model for \(\eta = 3(1 + \alpha)\) and \(w = -1\) (Bento, Bertolami & Sen 2004), \(\alpha\) being the GGG equation of state parameter, \(p = -A/\rho^\alpha\), where \(A\) is a positive constant.

### 3 GAMMA-RAY BURSTS

In this work, one considers the Amati \(E_{\text{iso}}-E_{\text{iso}}\) correlation (for a discussion of the use of other correlations, see for instance Bertolami & Tavares 2006 and Liang & Zhang 2006). This correlation can be used to place constrains on the Hubble diagram. The sample provided in Amati et al. (2008) and Amati, Frontera & Guidorzi (2009) that includes the observations of 95 GRB with measurements for \(E_{\text{iso}}\), \(E_{\text{iso}}\) and redshift, is adopted.

The value of \(E_{\text{iso}}\) is an observable quantity, independent of a cosmological model. On the other hand, \(E_{\text{iso}}\) is computed for each GRB from its spectral parameters, fluence and redshift using a specific cosmological model. [The \(E_{\text{iso}}\) presented in Amati et al. (2008, 2009) is computed in the context of the ΛCDM scenario with \(h = 0.7\), \(\Omega_{\text{DM0}} = 0.3\) and \(\Omega_{\text{DE0}} = 0.7\).]

The Amati correlation assumes a power-law relationship between \(E_{\text{iso}}\) and \(E_{\text{iso}}\). A cosmological model can then be tested comparing the \(E_{\text{iso}}\) computed from the observations with a theoretical \(E_{\text{iso}}\) obtained from \(E_{\text{iso}}\). In practice, however, since the \(E_{\text{iso}}-E_{\text{iso}}\) relationship is not calibrated, one has to simultaneously fit for the power-law parameters.

Furthermore, following Amati (2006), the scatter of the \(E_{\text{iso}}-E_{\text{iso}}\) relation that cannot be explained by statistical fluctuations alone must be taken into account. As in D’Agostini (2005) and Amati (2006), this is done by introducing a third parameter, an extrinsic...
variance, $\sigma_{\text{ext}}$, in the fitting of the data. Using a power law $E_{\text{iso}} = E_{\text{iso}} \log q$, one aims to minimize the likelihood function, where

$$x^2_{\text{GRB}} = -\sum_{\text{objects}} \left[ \log(2\pi\sigma^2) + \frac{(\log E_{\text{iso}} - m \log E_{\text{iso}} - q)^2}{\sigma^2} \right],$$

and the total variance is $\sigma^2 = \sigma^2_{\text{ext}} + \sigma^2_{\text{p}} + m^2\sigma^2_{\text{iso}}$, where $\sigma_p$ and $\sigma_{\text{iso}}$ are the observational variances on $\log E_{\text{iso}}$ and $\log E_{\text{iso}}$, respectively. The fit is performed for the three parameters $m, q$ and $\sigma_{\text{ext}}$. This minimization is then carried out for different values of the cosmological parameters, resulting in a profile of the likelihood function.

### 3.1 Generating a GRB mock sample

Given that the GRB data are currently rather limited, the analysis is extended to include a mock sample of GRBs in order to test the efficiency of the Amati relation on constraining dark energy and dark matter interacting models. The goal is to check the effect of a larger number of GRBs, but also the effect of higher redshift GRBs. From 2009 onwards, most of the useful events to fit the Amati relation came from the Swift and Fermi experiments. One can expect from these experiments approximately 10 useful GRB events per year. The future launch of the EXIST mission, scheduled for 2017, will considerably improve this rate, hopefully simultaneously reducing the measurement errors. This paper settles on a best case scenario of 500 GRBs events but conservatively keeping the error bars at the present level.

Following Amati et al. (2008), a distribution mimicking the observed GRB redshift distribution in the range $0 < z < 6$ is used. A chosen percentage of these events was then replaced with redshifts uniformly distributed in the range $6 < z < 10$. This allows for a tuning of the number of high-redshift GRBs in the mock sample that is used in the fits. Note that different choices on the shape of the high-redshift distribution of GRBs is approximately equivalent to a change on the redshift cut-off value and its percentage. Ultimately, only a significant number of high-redshift GRBs can yield a sizable restriction on $\epsilon_0$. The details about the actual low-redshift distribution used to generate the mock data are discussed in the Appendix A.

Once a redshift distribution is obtained, lognormal distributed values of $E_{\text{iso}}$ are attributed to each data point and are associated with a power law related $E_{\text{iso}}$. In this paper, a value of 5.86 for $\log(E_{\text{iso}}/1\text{ keV})$ is used for the mean and a value of 1 is used for the variance. An extrinsic variance (using $\sigma_{\text{ext}} = 0.41$) and Gaussian errors for $E_{\text{iso}}$ and $E_{\text{iso}}$ (20 per cent for both) are then included, mimicking the current observational situation. It is verified that the results are not particularly sensitive to these choices. Several mocks with a varying number of low- and high-redshift GRBs were generated and studied. The presented results consist of a typical mock sample with 500 events generated and 10 per cent of high-redshift GRBs, in a CDM universe.

### 4 Cosmological Data

In order to gauge to which extent GRB data can constrain cosmological parameters, one confronts it with other well-known cosmologically relevant observational tests such as SNe, BAO and the CMBR shift parameter.

### 4.1 Supernovae

The SNe sample from the Sloan Digital Sky Survey II (SDSS-II) first-year results (Kessler et al. 2009) is used, consisting of 288 SNe Ia with redshifts up to 1.55. SNe are used as distance indicators by comparing the theoretical distance modulus, $\mu_{\text{th}}$, obtained from the measured redshift in a given model of cosmological evolution, and with the inferred distance modulus, $\mu_{\text{obs}}$, computed from fits to the SNe light curves (using the data of the mlsC2k2 fits found in Kessler et al. 2009).

Specifically, the theoretical distance modulus is given by

$$\mu_{\text{th}} = 5 \log D_L + 5 \log \left( \frac{c}{H_0} \right) + 25,$$

with $D_L$ being the scaled ($H_0$ independent) luminosity distance in Mpc, $D_L(z) = (1 + z) \int_0^z \frac{dz'}{E(z')}$. For each cosmological parameter choice, the used likelihood is given by

$$x^2_{\text{SN}} = \sum_{\text{SN objects}} \frac{(\mu_{\text{obs}} - \mu_{\text{th}})^2}{\sigma_{\text{th}}^2},$$

where $\sigma_{\text{th}}^2 = \sigma_{\text{th}}^2 + \sigma_{\text{disp}}^2 + \sigma_{\text{ext}}^2$ is the measurement variance for $\mu_{\text{obs}}$, including the error from the fit, an intrinsic dispersion error of $\sigma_{\text{disp}} = 0.16$ and a redshift error to account for the host galaxy peculiar movement and spectroscopic measurement. Only the SNe results are marginalized over $H_0$ with a flat prior; all the other constraints assume a constant $h = 0.7$.

### 4.2 Baryon acoustic oscillations

One also considers the constraints from the effect of the baryon acoustic peak of the large-scale correlation function at 100 $h^{-1}$ Mpc separation detected by the SDSS luminous red galaxy sample (Moldenhauer & Ishak 2009; Reid et al. 2010). The peak position is related to the quantity

$$A = \sqrt{\Omega_M} E(z)_{1/3} \left[ \frac{1}{c_1} \int_0^{z_1} \frac{dz'}{E(z')} \right]^{2/3},$$

measured to be $A_0 = 0.493$, with an error of $\sigma_A = 0.017$. The used likelihood is given by

$$x^2_{\text{BAO}} = \left( \frac{A_0 - A}{\sigma_A} \right)^2.$$

### 4.3 Cosmic microwave background radiation shift parameter

Here, the constraints from the CMBR Wilkinson Microwave Anisotropy Probe seven (WMAP7) observations (Komatsu et al. 2010) are considered. The shift parameter (Bond, Efstathiou & Tegmark 1997) can be used as a distance prior to constrain a given dark energy model. The shift parameter is given by the equation

$$R_{\text{th}} = \frac{D_L(z_*)}{(1 + z_*)} \sqrt{\Omega_M},$$

with $D_L$ being the luminosity distance defined in equation (11), and $z_*$, the redshift at decoupling. The standard fitting formula for $z_*$ is used (Hu & Sugiyama 1996). This theoretical prediction is then constrained through the fitted WMAP7 observation, $R_{\text{obs}} = 1.725$ with error $\sigma_R = 0.018$, through

$$x^2_{\text{CMB}} = \left( \frac{R_{\text{th}} - R_{\text{obs}}}{\sigma_R} \right)^2.$$
5 RESULTS AND CONSTRAINTS

One starts with the constraints obtained from the real observed 95 GRBs data (Amati et al. 2008, 2009), combined with the SNe SDSS-II data (Kessler et al. 2009). For this, $\Omega_{\text{M_0}} = \Omega_{\text{DM_0}} + \Omega_{\text{b_0}}$ is fixed at $\Omega_{\text{M_0}} = 0.3$ with $\Omega_{\text{b_0}} = 0.0445$ and the Hubble parameter held at $h = 0.7$. The result can be seen in Fig. A1. At 68 per cent confidence level, the SNe data alone provides the limits $\zeta_0 \in [-1.93, 1.02]$ and $w \in [-1.07, -0.62]$. These results are, by themselves, highly degenerate in $\zeta_0$. Including the GRB real data, one improves slightly the constraints to $\zeta_0 \in [-1.15, 1.66]$ and $w \in [-0.94, -0.58]$. As expected, the status of the GRB data at present does not allow for a significant improvement over the SNe constraints on these two parameters (see Fig. A1). This SNe degeneracy is usually lifted combining the SNe data with the CMBR WMAP7 shift parameter observations yielding the bounds $\zeta_0 \in [-0.01, 0.13]$ and $w \in [-0.83, -0.65]$ at 68 per cent confidence level (not shown).

Even though the present GRB data cannot compete with these CMBR constraints, with additional data they can provide an important independent method of lifting the SNe degeneracy in $\zeta_0$. It must be stressed that these results are obtained for $\Omega_{\text{M_0}}$ fixed at 0.3.

To illustrate this point, a mock population is chosen in order to show what can be accomplished from a large population of GRBs, despite the current level of measurement and theoretical uncertainties. A $\Lambda$CDM universe has been used to generate a mock sample (see Section 3.1). This time, the results are marginalized over $\Omega_{\text{M_0}}$ with a flat prior in the interval $0.2 \leq \Omega_{\text{M_0}} \leq 0.4$. In Fig. A2, the results of the SNe and GRB constraints are shown. The constraints obtained are $\zeta_0 \in [-0.21, 0.82]$ and $w \in [-0.84, -0.58]$, at 68 per cent confidence level. From the SNe data alone, only a lower bound can be derived for $\zeta_0$, in the considered parameter range.

Once again, this SNe degeneracy in $\zeta_0$ can be lifted by combining the SNe and CMBR constraints, yielding the bounds $\zeta_0 \in [-0.29, 0.18]$ and $w \in [-1.08, -0.65]$ at 68 per cent confidence level. Fig. A3 combines all the available constraints, namely GRB, SNe, BAO and CMBR. The CMBR data clearly provides the tighter constraints on all the parameters. It is, however, highly degenerate in $w$ and, hence, the SNe constraints on $w$ are required to yield significant bounds. Notwithstanding, the GRB data have a similar profile to the CMBR bounds, and they can provide a significant bound in $\zeta_0$. Thus, GRB data, in combination with SNe, provide an independent and compatible constraint on $\zeta_0$ and $w$. On the other hand, the BAO result clearly does not yield a strong constraint on the value of either $w$ or $\zeta_0$ (as opposed to the SNe data), and does not significantly improve the results obtained from GRBs or CMBR. The overall combined results give the bounds $\zeta_0 \in [-0.10, 0.08]$ and $w \in [-0.89, -0.70]$ also at 68 per cent confidence level.

The GRB constraint on $\zeta_0$ comes mostly from its high-redshift valued data, whereas the low-redshift valued SNe data present a degeneracy in $\zeta_0$. Note however that for the GRB and CMBR data, one encounters a degeneracy in $\zeta_0$ in the form of a bend occurring at $\eta < 0$ (i.e. $\zeta_0 > -3w \Omega_{\text{DM}}$). This occurs as for negative $\eta$ and for high $z$, the evolution is dominated by the dark energy density, rendering the luminosity distance virtually independent of $\eta$.

6 DISCUSSION AND CONCLUSIONS

In this work, the use of GRBs as cosmological tools is considered. It has been shown (Bertolami & Tavares 2006; Amati et al. 2008) that GRBs have a great potential to measure the value of $\Omega_{\text{DM}}$ independently from the CMBR constraints. In the current work, it is shown that the present GRB data already give a better constraint on the dark energy and dark matter coupling parameter $\zeta_0$ than the BAO results. The SNe results provide good bounds on $w$, but are more degenerate in $\zeta_0$. Despite of that, the experimental GRB sample is still too small to provide significant constraints on $\zeta_0$.

The combined result for SNe and real GRB data further illustrates this, yielding $\zeta_0 \in [-1.15, 1.66]$, with a width of $\Delta \zeta_0 = 2.81$, as opposed to the combined SNe and CMBR data limit $\zeta_0 \in [-0.01, 0.13]$ ($\Delta \zeta_0 = 0.14$), both at 68 per cent confidence level. These results are obtained without marginalization, for fixed $\Omega_{\text{M_0}} = 0.3$.

A mock population of GRBs was then generated showing that as the number of available events increases, GRB data becomes a more and more valuable tool in constraining the parameter $\zeta_0$. The GRBs complement the SNe constraint in a similar way the CMBR does. For a fixed $\Omega_{\text{M_0}} = 0.3$, the SNe and mock GRB data yield $\Delta \zeta_0 = 0.82$.

For a deeper insight on the future cosmological implications of the GRB observations, the analysis was extended to a marginalization over $\Omega_{\text{M_0}} \in [0.2, 0.4]$. The combined SNe and CMBR results are $\Delta \zeta_0 = 0.47$ (68 per cent confidence level), while for SNe and the mock GRB yield $\Delta \zeta_0 = 1.03$. Granting that the obtained bounds are not as accurate as the CMBR ones, they still provide a valuable independent measurement of these cosmological parameters.

With the same marginalization in $\Omega_{\text{M_0}}$, the combined result for SNe, CMBR and BAO is $\zeta_0 \in [-0.27, 0.13]$ (95 per cent confidence level). The updated observations improve the previous result $\zeta_0 \in [-0.4, 0.1]$ (Guo, Ohta & Tsujikawa 2007). Note, however, that tighter priors are used in this work and that this model is slightly different, with the inclusion of non-interacting baryonic matter.

It is interesting to compare the present results with the ones arising from estimates of the departure from the virial equilibrium of the Abell cluster A586. The bounds for $\eta$ from the Abell Cluster A586 yield $\eta \in [3.65, 4.00]$ ($\Delta \eta = 0.35$, with $w = -1$ and $z = 0.1708$ and $\Omega_{\text{M_0}} = 0.28$, (Bertolami et al. 2007). Using SNe and mock GRB data from the present work and fixing $\Omega_{\text{M_0}} = 0.28$, one encounters $\eta \in [0.93, 2.48]$ ($\Delta \eta = 1.55$) at 68 per cent confidence level. If one considers the particular case of the GCG, the Abell Cluster A586 limits the $\alpha$ parameter to $\alpha \in [0.21, 0.33]$ (68 per cent confidence level). This compares with the combined SNe and mock GRB results, $\alpha \in [0.25, 0.83]$ (68 per cent confidence level).

One should bear in mind that the GRB results were obtained from a mock population and are, thus, only indicative of what can be expected when the number of observed GRBs increases. The limits for $\alpha$ with the current observational SNe and CMBR data yield $\alpha \in [0.03, 0.06]$.

In this work, the Amati correlation (Amati et al. 2008) has been used, given that it requires only two parameters whose determination can be inferred and increasing the number of useful GRB events available. Progress in the calibration and on the theoretical framework of this calibration would be invaluable, reducing the error margins in the GRB data and considerably improving the constraints on the parameters.

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APPENDIX A: GRB MOCK DATA

For the mock sample generation, the following distribution is considered (Porciani & Madau 2001):

\[
\begin{align*}
\frac{dN(P_1 \leq P \leq P_2)}{P_2 - P_1} &= \frac{dV(z)}{dz} \frac{R_{\text{GRB}}(z)}{1 + z} \int_{P_1, z} \psi(L') e(P), \\
\end{align*}
\]

(A1)

Figure A1. Constraints on the values of \( w \) and \( \zeta_0 \) obtained from the SNe data (dashed line) and its combination with the 95 GRB data (full line). The 68 and 90 per cent confidence levels are depicted. One fixes \( \Omega_M = 0.3 \) and \( h = 0.7 \).

Figure A2. Constraints on the values of \( w \) and \( \zeta_0 \) obtained from SNe and a mock of 500 GRB population. The wider contour in \( w \) corresponds to the GRBs (in green, for online readers) and the wider contour in \( \zeta_0 \) to the SNe (in red, for online readers). Both 68 per cent and 95 per cent confidence levels are shown. The shaded area refers to the combined confidence region. A marginalization over \( \Omega_M \in [0.2, 0.4] \) has been considered.

Figure A3. The combined constraints on the values of \( w \) and \( \zeta_0 \) obtained from the SNe (red), BAO (light blue), CMB (blue) and a mock 500 GRB population (green). The GRB and SNe contours are the same as in Fig. A2. The CMB contour is the narrower one (in blue) and the BAO contour is in background (light blue). The dark patch shows the combined region. The 68 and 95 per cent confidence levels are shown. A marginalization over \( \Omega_M \in [0.2, 0.4] \) has been carried out.

where \( dV/dz \) is the comoving volume element, \( R_{\text{GRB}} \) is the comoving GRB rate density and \( e(P) \) is the detector efficiency as a function of photon flux. The quantity \( \psi(L) \) is the normalized GRB luminosity function and \( L \) is a ‘isotropic equivalent’ burst luminosity \( L = \int_{300\text{keV}}^{2000\text{keV}} E \, S(E) \, dE \), for the energy \( E \) and \( S(E) \) is the rest-frame photon luminosity of the source.

The generation process is performed as follows: using a Monte Carlo generator, a sample of the desired number of GRBs with \( z \) in the range \( 0 < z < 6 \) is generated, using equation (A1). Then, a desired percentage is replaced randomly by events in the range \( 6 < z < 10 \), using a flat distribution. The \( E_{\text{iso}} \) is randomly attributed according to a Gaussian distribution and \( E_{\text{iso}} \) is then calculated using a power law with the parameters calculated using a fit of the real GRB sample. The errors are added afterwards assuming a Gaussian distribution.

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