Astronomical and Astrophysical Transactions (*AApTr*), 2016, Vol. 29, Issue 2, pp. 193–204,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

GRB cosmology through the $E_{\rm p,i}$–intensity correlation

Lorenzo Amati[1,2,*], Disha S. Sawant[3,1,2], Massimo Della Valle[4,2]

[1]*INAF–IASF Bologna, via P. Gobetti 101, 40129 Bologna, Italy*
[2]*ICRANet, Piazzale della Repubblica 10, 65122 Pescara, Italy*
[3]*University of Ferrara, Via Saragat-1, Block C, Ferrara 44122, Italy*
[4]*INAF–Osservatorio di Capodimonte, Salita Moiariello, 16, 80131 Napoli, Italy*

Received 15 December, 2015

Despite they are not standard candles, the investigation of Gamma-Ray Bursts (GRBs) as a tool for measuring the geometry and expansion rate of the Universe is strongly motivated by their unique combination of huge luminosity, up to more than 10^{53} erg/s, with a redshift distribution extending up to more than $z = 9$. In recent years, several attempts to exploit the correlation between the photon energy at which the νF_ν spectrum peaks (*peak energy*) and the radiated energy (or luminosity) for standardizing GRBs and using them to estimate cosmological parameters have been made. These studies show that already with the present data-set, GRBs can provide a significant and independent confirmation of $\Omega_{\rm M} \sim 0.3$ for a flat ΛCDM. The investigation of the correlation of $E_{\rm p,i}$ with different intensity indicators (e.g., radiated energy, average and peak luminosity, bolometric vs. monochromatic quantities, etc.) both in terms of intrinsic dispersion of and accuracy for estimating $\Omega_{\rm M}$ further confirms its reliability and effectiveness for both GRB physics and their standardization for cosmology. Current (e.g., *Swift*, *Fermi*/GBM, Konus–WIND) and forthcoming GRB experiments (e.g., CALET/GBM, SVOM, Lomonosov/UFFO) will allow us to constrain $\Omega_{\rm M}$ with an accuracy comparable to that currently exhibited by Type Ia supernovae and to study the properties of dark energy and their evolution with time.

Keywords: Cosmological parameters – gamma-rays: bursts – gamma rays: observations

1 Introduction

The evidence, emerged at the end of the '90s, that we are living in a flat Universe undergoing accelerated expansion and in which the baryonic matter contributes only a small fraction (∼4–5%) of the total matter-energy density is mostly based on combined observations of high redshift type Ia supernovae (SNe Ia) and of the Cosmic Microwave

*Email: amati@iasfbo.inaf.it

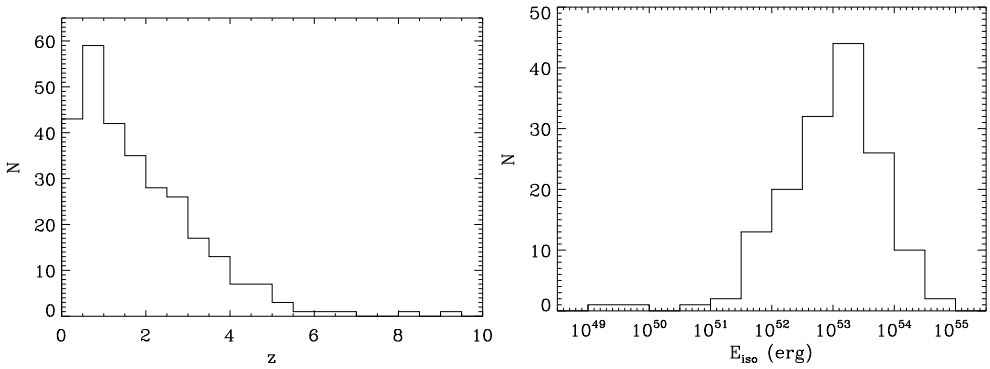


Figure 1 Distributions of redshift and isotropic-equivalent radiated energy, $E_{\rm iso}$, of long GRBs (until the end of 2013).

Background (CMB). Other complementary probes like Galaxy Clusters and Baryonic Acoustic Oscillations (BAO) further support this scenario.

However, each of these probes is affected by specific systematics, which may bias significantly the estimate of cosmological parameters, like the matter density $\Omega_{\rm M}$, the dark energy density Ω_Λ and the equation of state (EoS) of the dark energy. More probes are available and more cross-checks among the results obtained with each of them can be done, thus minimizing the effects of the systematics of single probes. In addition, each different class of probes has a different "sensitivity" to cosmological parameters depending on its redshift distribution. Thus, the search for more classes of sources that can be used as standard candles to study the geometry and the evolution of the expansion rate of the Universe is highly motivated.

With an observed redshift distribution extending from 0.0085 (GRB 980425) up to 8.26 (GRB 090423) or ∼9.2 if we include photometric redshift (GRB 090429B) and isotropic-equivalent radiated energies up to more than $\sim 10^{54}$ erg, released typically in a few tens or hundreds of seconds (Fig. 1), Gamma-Ray Bursts (GRBs) are the brightest cosmological sources in the Universe. In addition, they emit most of their radiation in the hard X-rays, thus, contrary to SNe Ia, they are not affected by dust absorption. Unfortunately, they are not standard candles, given that their radiated energies, or luminosities, span several orders of magnitude. However, as we discuss in the next Sections, the recent discovery of a strong correlation between the photon energy at which the νF_ν spectrum peaks and the GRB intensity has opened to us the possibility of standardizing these sources in a way similar to SNe Ia and using them as cosmological probes.

2 The correlation between GRB spectral peak energy and intensity

GRBs show non-thermal spectra which can be empirically modeled with so-called Band function, i.e., a smoothly broken power law with parameters the low-energy spectral index α, the high energy spectral index β and the "roll-over" energy E_0. As can be seen in Fig. 2, when converted into νF_ν, i.e., the distribution of the emitted

energy as a function of photon energy, the spectrum shows a peak; the photon energy at which this peak occurs is a characteristic quantity in GRB emission models and is called *peak energy*, $E_{\rm p}$. Since the late '90s, thanks to the first discoveries of GRBs optical counterpart and host galaxies and the measurement of their redshift, it has been possible, for a small fraction of GRBs, to convert the observed spectrum into a rest-frame spectrum. This allowed the estimate of two key intrinsic quantities: the total radiated energy computed by integrating the spectrum in a standard (1–10000 keV) energy band and assuming isotropic emission, $E_{\rm iso}$, and the peak energy of the cosmological rest-frame νF_ν spectra of GRBs, $E_{\rm p,i} = E_{\rm p} \times (1+z)$. As of the end of 2013, the number of GRBs with measurements of the redshift and of the spectral parameters accurate enough to allow a reliable computation of $E_{\rm p,i}$ and $E_{\rm iso}$, is ∼160. The distribution of $E_{\rm p,i}$ for these events is approximately a Gaussian centered at a few hundreds of keV and with a low energy extension down to a few keV, corresponding to the so-called X-Ray Flashes (XRFs) or X-Ray Rich (XRR) events. Whether this distribution is significantly biased by instrumental effects or is an intrinsic property of GRBs is still unclear, in particular concerning the real fraction of XRFs and XRRs with respect to "normal GRBs". The distribution of $E_{\rm iso}$ is somewhat similar, extending from $\sim 10^{51}$ to more than $\sim 10^{54}$ erg, peaking at $\sim 10^{53}$ erg and with a few peculiar weak events ($\sim 10^{48}$–$\sim 10^{50}$ erg).

In 2002, based on a small sample of *Beppo*SAX GRBs with known redshift and spectral parameters, it was discovered (Amati et al., 2002) that $E_{\rm p,i}$ is significantly correlated with $E_{\rm iso}$. This correlation, commonly called *Amati relation* within the GRB community, has the form

$$\log E_{\rm p,i}({\rm keV}) = m \log E_{\rm iso}(10^{52}{\rm erg}) + q\,,$$

with $m \sim 0.5$ and $q \sim 2$, and is characterized by an extra-Poissonian scatter normally distributed with a $\sigma_{\rm ext}$ of ∼0.2 dex around the best-fit law. Subsequent observations with various detectors and spectrometers confirmed and extended the $E_{\rm p,i}$–$E_{\rm iso}$ correlation, showing that it holds for all long GRBs and XRFs with well measured redshift and spectral parameters (Amati 2006, Amati et al. 2008). The present distribution

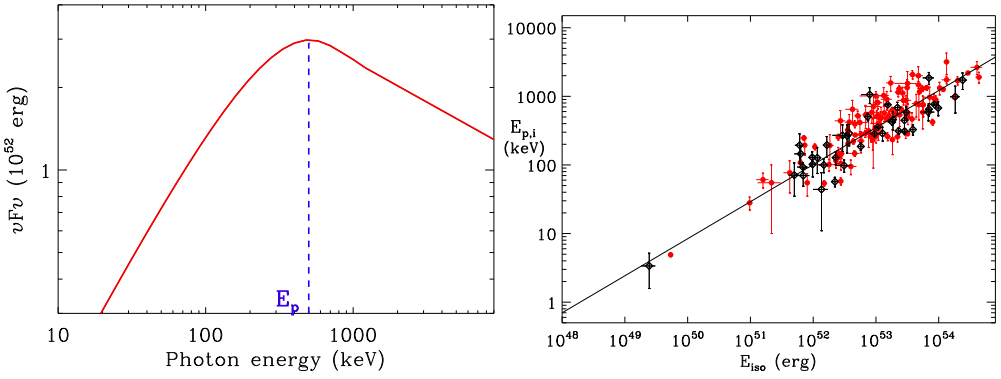


Figure 2 Left: typical νF_ν (energy) spectrum of a GRB in its cosmological rest-frame. Right: the $E_{\rm p,i}$–$E_{\rm iso}$ correlation in long GRBs (as of the end of 2013). The black line shows the best-fit power law.

of long GRBs and XRFs in the $E_{\rm p,i}$–$E_{\rm iso}$ plane is shown in Fig. 2; part of the plotted data, together with the power-law best-fitting the long GRBs points and its confidence region, have been taken from Amati et al. (2008) and Amati et al. (2009).

For more recent bursts, the $E_{\rm p,i}$–$E_{\rm iso}$ and $E_{\rm p,i}$ values were computed. These values are based on spectral data and fluences reported in the GCN Circulars (gcn.gsfc.nasa.gov/gcn3_archive.html) by following the method outlined, e.g., in Amati et al. (2002) and Amati (2006). The existence, properties (slope and dispersion) and extension over several orders of magnitude in both $E_{\rm p,i}$ and $E_{\rm iso}$ of the correlation are challenging observational evidences for the models of the physics and geometry of the prompt emission of GRBs (e.g., Zhang & Mészáros, 2002; Lamb et al., 2004; Amati, 2006).

3 GRB cosmology through the $E_{\rm p,i}$-intensity correlation

As discussed in the Introduction, finding new classes of sources suitable to complement present cosmological probes (e.g., SNe Ia, galaxy clusters, or BAO) in the measurement of the geometry and expansion history of the Universe, is of paramount importance for modern cosmology. In this respect, GRBs are of very high interest, because of their huge luminosities (not absorbed in X-rays, as already mentioned) that extend the redshift distribution much above that of SNe Ia, galaxy clusters and BAO. Since the $E_{\rm p,i}$–$E_{\rm iso}$ correlation correlates the quantity $E_{\rm p,i}$ (which is independent of the cosmological model), with the quantity $E_{\rm iso}$ (whose computation requires the luminosity distance $D_{\rm L}$), then it could theoretically be used to "standardize GRBs", in a way similar to the use of the Phillips relation (Phillips 1993) to standardize SNe Ia.

However, the significant extra-Poissonian scatter of the correlation (Amati et al. 2008) and the lack of a sufficient number of very low redshift GRBs allowing a cosmological-independent calibration, prevented for several years the use of the correlation for this purpose.

The investigations of GRBs as cosmological probes started in 2004, when evidence was found (Ghirlanda et al., 2004; Dai et al., 2004) that the $E_{\rm p,i}$–$E_{\rm iso}$ correlation tightens by substituting $E_{\rm iso}$ with the collimation-corrected radiated energy $E_\gamma = (1-\cos\theta_{\rm jet}) \times E_{\rm iso}$. This result was based on a small sub-sample of GRBs with known $E_{\rm p,i}$ and $E_{\rm iso}$ for which it was possible to infer the jet opening angle $\theta_{\rm jet}$ from the *break time*, $t_{\rm b}$, at which the decay index of the light curve of the optical afterglow sharply changes to a steeper one, under the assumption of a simple jet and afterglow model (Sari et al., 1999). By exploiting the low scatter of the $E_{\rm p,i}$–E_γ correlation and applying statistical methods accounting for the lack of calibration (the so called *circularity problem*), it was possible to derive, within the standard ΛCDM cosmological model, estimates of $\Omega_{\rm M}$ and Ω_Λ consistent with the "concordance" values mostly coming from the analysis of SNe Ia and the CMB. A review of these methods and results is provided in Ghirlanda et al. (2006). The results of these investigations were encouraging, and prompted other studies aimed at deriving a GRB Hubble diagram, based, e.g., on the joint use of the $E_{\rm p,i}$–E_γ correlation together with other weaker correlations between luminosity and observed properties (Schaefer, 2007), or the calibration of the $E_{\rm p,i}$–E_γ correlation with SNe Ia (e.g., Kodama et al., 2008; Demianski et al., 2008).

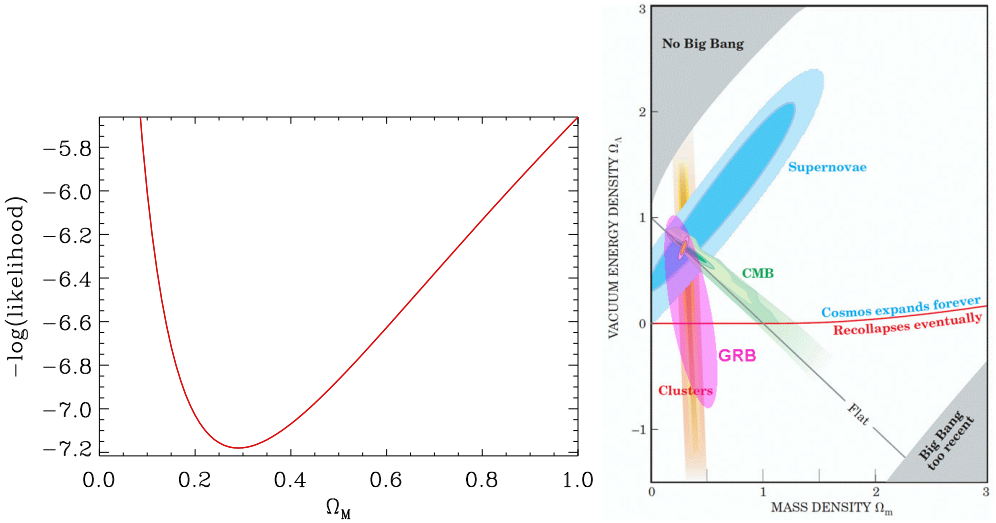


Figure 3 Left: goodness of fit of the $E_{p,i}$–E_{iso} correlation of long GRBs, expressed in terms of $-log$ (likelihood), as a function of the value of Ω_M used to compute the E_{iso} values in a standard ΛCDM flat universe. Right: 68% confidence level contour in the Ω_M–Ω_Λ plane obtained by releasing the flat Universe assumption and assuming a sample of sample of 250 GRBs expected in the near future (see Table 1 and text) compared to those from other cosmological probes (adapted from a figure by the Supernova Cosmology Project; Suzuki et al., 2012). From Amati & Della Valle (2013).

However, in the last years, the simple jet model assumed to compute θ_{jet} from the break time of the optical afterglow light curve has been seriously challenged by the observed different behavior of the X-ray afterglow light curves, which, in several cases, show no *jet-break* or show a break not simultaneous to the optical one. This makes the determination of E_γ, and thus the characterization and use of the $E_{p,i}$–E_γ correlation, less firm.

Thus, a recent work (Amati et al., 2008) investigated the possibility of using, for the estimate of cosmological parameters, the simple $E_{p,i}$–E_{iso} correlation, which, w/t the $E_{p,i}$–E_γ correlation, has the advantage of allowing the use of a sample about four times larger, and is based on only two observables (the $E_{p,i}$–E_γ correlation requires, in addition to E_{iso} and $E_{p,i}$, also t_b) and avoids the model-dependent assumptions (jet model, afterglow model, density and profile of the circum-burst environment, efficiency of conversion of fireball kinetic energy into radiated energy) which affect the computation of E_γ. It was found that, by assuming a flat ΛCDM Universe, the χ^2 obtained by fitting the correlation with a simple power law is a function of the value of Ω_M assumed in the computation of E_{iso}.* In particular, as can be seen in Fig. 3, where we show the result obtained for a sample of 156 GRBs available as of the end of 2012, the function $\chi^2(\Omega_M)$ shows a parabolic shape with a minimum at $\Omega_M \sim 0.25$–0.30. This is a simple but relevant result: a) it shows that the $E_{p,i}$–E_{iso} correlation can indeed be used to extract information on cosmological parameters;

*This result was originally based on the sample of 70 long GRBs with known $E_{p,i}$ and E_{iso} published by Amati et al. (2008).

Table 1 Comparison of the 68% confidence intervals on $\Omega_{\rm M}$ and w_0 ($\Omega_{\rm M} = 0.3$, $w_{\rm a}= 0.5$; a standard parametrization of the dark energy equation of state: $w = w_0 + w_{\rm a} z/(1+z$ was assumed) for a flat Friedmann–Lemaître–Robertson–Walker (FLRW) universe obtained with the sample of 70 GRBs by Amati et al. (2008), the sample of 156 GRBs available as of the end of 2012 and simulated samples of 250 and 500 GRBs (Amati & Della Valle, 2013). In the last three lines are also shown the results obtained for the same samples by assuming that the slope and normalization of the $E_{\rm p,i}$–$E_{\rm iso}$ correlation are known with a 10% accuracy based, e.g., on calibration against SNe-Ia or self-calibration with a large enough number of GRBs at similar redshift.

GRB #	$\Omega_{\rm M}$ (flat)	w_0 (flat, $\Omega_{\rm M} = 0.3$, $w_{\rm a}= 0.5$)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$	< -0.3 (90%)
156 (real) GRBs (Amati & Della Valle, 2013)	$0.29^{+0.28}_{-0.15}$	$-0.9^{+0.4}_{-1.5}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$	$-0.9^{+0.3}_{-1.1}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
156 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
250 (156 real + 94 simulated) GRBs, calibration	$0.30^{+0.04}_{-0.05}$	$-1.1^{+0.20}_{-0.20}$
500 (156 real + 344 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$

b) it provides evidence, independently from SNe Ia or other probes, that, if we live in a flat Universe as predicted by many inflationary models and supported by CMB measurements, the density of the Universe is dominated by an unknown component (e.g., dark energy).

Given the significant extra-Poissonian scatter of the correlation, the simple χ^2 method cannot be used to obtain reliable confidence levels on both the parameters of the correlation (normalization and slope) and the cosmological parameters. To this purpose, in Amati et al. (2008) it was adopted a maximum likelihood method accounting for the uncertainties on both the X and Y quantities and the extra variance $\sigma_{\rm ext}$. In Table 1, we show the 68% and 90% c.l. intervals for $\Omega_{\rm M}$, in the assumption of a flat Universe, obtained in this way with the sample of 70 GRBs used by Amati et al. (2008) and the 156 GRBs available at the end of 2012. As can be seen, by increasing the number of GRBs in the sample the accuracy of the estimate of $\Omega_{\rm M}$ improves. This is confirmed also by the investigation of the confidence contours in the $\Omega_{\rm M}$–Ω_Λ plane computed by following the same method as above but releasing the flat Universe assumption. The 68% confidence region obtained with the present 156 GRBs is smaller than that corresponding to the 70 GRBs by Amati et al. (2008).

4 Correlation of $E_{\rm p,i}$ with different "intensity" indicators

Soon after the discovery of the $E_{\rm p,i}$–$E_{\rm iso}$ correlation, it was pointed out that $E_{\rm p,i}$ correlates as well with other "indicators" of GRB "brightness" like, e.g., the peak luminosity. In order to investigate the best tool for standardizing GRBs, Sawant & Amati (2015) analyzed the correlation of $E_{\rm p,i}$ with different intensity indicators: $E_{\rm iso}$, the total radiated energy, computed by integrating the spectrum in a standard energy

Table 2 Cosmological parameters from various $E_{\rm p,i}$–intensity correlations as derived by Sawant & Amati (2015) based on a sample of 182 GRBs up to the end of 2014.

Correlation	$\Omega_{\rm M}$ with 68% C.L.
$E_{\rm p,i}$–$E_{\rm iso}$ bolometric	$0.24\ ^{+0.23}_{-0.12}$
$E_{\rm p,i}$–$L_{\rm iso}$ for exposure time	$0.27\ ^{+0.40}_{-0.16}$
$E_{\rm p,i}$–$E_{\rm iso}$ monochromatic	$0.25\ ^{+0.24}_{-0.12}$

band and assuming isotropic emission; $L_{\rm iso_{T90}}$, *The isotropic luminosity averaged over the T90 duration*: The T90 duration, in seconds, is the time computed during which 90% of the burst fluence was accumulated. The start of the T90 interval is defined by the time at which 5% of the total fluence has been detected and the end of the T90 interval is defined by the time at which 95% of the fluence been detected; $L_{\rm iso_{Exp}}$, *The isotropic luminosity averaged over the exposure time*: The time interval (in seconds relative to trigger time) used in the spectral fits over the duration of the burst; $L_{\rm p}$, The luminosity computed at the peak of the spectra. All the quantities were computed over "bolometric" (in the commonly used 1–10000 keV energy band in the cosmological rest frame) and also over "monochromatic" range (computed at the peak ($E_{\rm p}$) of the $\nu{\rm F}_\nu$ spectrum.

The fitting parameters of these various correlations (slope, normalization and dispersion) were computed by adopting the statistical method proposed by Reichart et al. (2001) which deals with fitting the data points affected by extrinsic scatter in addition to the statistical uncertainties. Some of the results are reported in Table 2. The $E_{\rm p,i}$–$E_{\rm iso}$ correlation still stands out to be the least scattered out of all the correlations considered. This can be explained mainly by the fact that $E_{\rm iso}$ automatically stresses on the fact that the brightest parts of a GRB are those determining the $E_{\rm p}$ value of the time-averaged spectrum. This is not considered for the average luminosity (either over exposure or T90) which is affected by the assumption that all the time bins of the GRB equally contribute to the resulting average $E_{\rm p,i}$. Finally, the computation of the peak luminosity (not shown here) is affected by non-homogeneous time scale and energy band over which it is computed, and hence produces a slightly more dispersed correlation with $E_{\rm p,i}$, both by using time-averaged spectrum and the spectrum measured at the peak of the light curve (available for a smaller fraction of GRBs).

The correlation of $E_{\rm p,i}$ with monochromatic quantities is less scattered with respect to what is found with the bolometric ones. This shows that a fraction of the dispersion is introduced by the extrapolation to a bolometric energy band due to the uncertainties on the fitting parameters α and β. While considering the average luminosity instead of total radiated energy, the merging of some of the short GRBs into the long GRBs' populated region is observed. This scenario may be pointing at the necessity of better understanding of classification of GRBs and also at their physical origin.

We also investigated the accuracy of each considered correlation for cosmology, by following the maximum likelihood method that takes into account the uncertainties in both the X and Y quantities and the extra variance $\sigma_{\rm ext}$ proposed by Reichart et

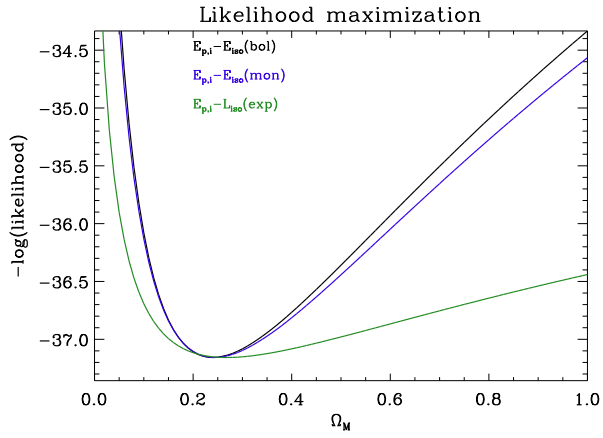


Figure 4 Likelihood maximization of different $E_{\rm p,i}$–intensity correlations as a function of $\Omega_{\rm M}$ for flat ΛCDM cosmology based on a sample of 182 GRBs as of December 2014 by Sawant & Amati (2015).

al. (2001) and the method established by Amati et al. (2008). Indeed, these authors found that, remarkably, the –log (likelihood) of the $E_{\rm p,i}$–$E_{\rm iso}$ as a function of the value of $\Omega_{\rm M}$ assumed for the computation of $E_{\rm iso}$ within a flat ΛCDM scenario shows a nice parabolic shape, with a minimum at $\Omega_{\rm M} \sim 0.30$ (Fig. 4).

We repeated the same analysis for all studied correlations. We observe that the dispersion of the correlations varies uniquely. Also, the minimization of $\Omega_{\rm M}$ varies but still remains considerably near to 0.3. For all the correlations $\Omega_{\rm M}$ shows a minimum around 0.3, although it is important to notice that for $E_{\rm p,i}$–$E_{\rm iso}$ correlations for both bolometric and monochromatic computations point out the minimization of $\Omega_{\rm M}$ more accurately. The distinctive advantage of considering monochromatic frame is that the fit results are independent on α and β and their uncertainties.

5 Further investigations and perspectives

Table 1 shows a sharp increase of the accuracy attached to $\Omega_{\rm M}$ as a consequence of the increasing number of GRBs in the $E_{\rm p,i}$–$E_{\rm iso}$ plane. Currently, the main contribution to enlarge the GRB sample comes from joint detections by *Swift*, *Fermi*/GBM or Konus-WIND. Hopefully, these missions will continue to operate in the next years, then providing us with an "actual" rate of ∼15–20 GRB/year. However, a real breakthrough in this field should come from next generation (>2017) missions capable of promptly pinpointing the GRB localization and of carrying out broad-band spectroscopy. We build our hopes, e.g., on the Japanese-led CALET/GBM experiment for the ISS (Yamaoka et al., 2009), the Chinese–French mission SVOM (Godet et al., 2012), the Lomonosov/UFFO (Grossan et al., 2012) experiment, an international project led by Korea and Taiwan. In Fig. 5 we show the confidence level contours in the $\Omega_{\rm M}$–Ω_Λ plane by using the real data as of 2012 and by adding to them 113 and 363 simulated GRBs (resulting in two samples of 250 and 500 GRBs in total,

respectively). The simulated data sets were obtained via Monte Carlo techniques by taking into account the slope, normalization and dispersion of the observed $E_{\rm p,i}$–$E_{\rm iso}$ correlation, the observed redshift distribution of GRBs and the distribution of the uncertainties in the measured values of $E_{\rm p,i}$ and $E_{\rm iso}$. These simulations indicate that with a sample of 250 GRBs (achievable in about 5 years from now) the accuracy in measuring $\Omega_{\rm M}$ will be comparable to that currently provided by SNe data.

Several authors (Kodama et al., 2008; Capozziello et al., 2010; Demianski et al., 2012) are investigating the calibration of the $E_{\rm p,i}$–$E_{\rm iso}$ correlation at $z < 1.4$ by using the luminosity distance versus redshift relation derived from SNe-Ia. The goal is to extend the SN-Ia Hubble diagram up to redshifts at which the luminosity distance is more sensitive to dark energy properties and evolution. The drawback of this approach is that, with this method, GRBs are no longer an independent cosmological probe.

Other approaches include: cosmographic calibration of the $E_{\rm p,i}$–$E_{\rm iso}$ correlation (Capozziello et al., 2010; Demianski et al., 2012); self-calibration of the correlation with a large enough number of GRBs lying within a narrow ($\Delta z \sim 0.1$–0.2) range of z (promising, but requires a significant sample enlargement); combining the $E_{\rm p,i}$–$E_{\rm iso}$ correlation with other (less tight) GRB correlations (Schaefer, 2007; Mosquera et al., 2008; Cardone et al., 2009); extending the $E_{\rm p,i}$–$E_{\rm iso}$ correlation by involving other prompt or afterglow properties (Dainotti et al., 2011; Izzo et al., 2015) aimed at reducing the dispersion of the correlation (but with the risk of increasing systematics and lowering the number of GRBs that can be used); testing alternative cosmologies vs. the standard ΛCDM model (Montiel et al., 2011; Freitas et al., 2011; Smale, 2011; Lu et al., 2011; Liang et al., 2011; Daiferio et al., 2011; Demianski et al., 2011; Capozziello et al., 2012; Cardone et al., 2012; Velten et al., 2013; Wei et al., 2013). Particularly promising are the perspectives of the self-calibration method, which will become feasible and accurate as the number of GRBs in the $E_{\rm p,i}$–$E_{\rm iso}$ plane will

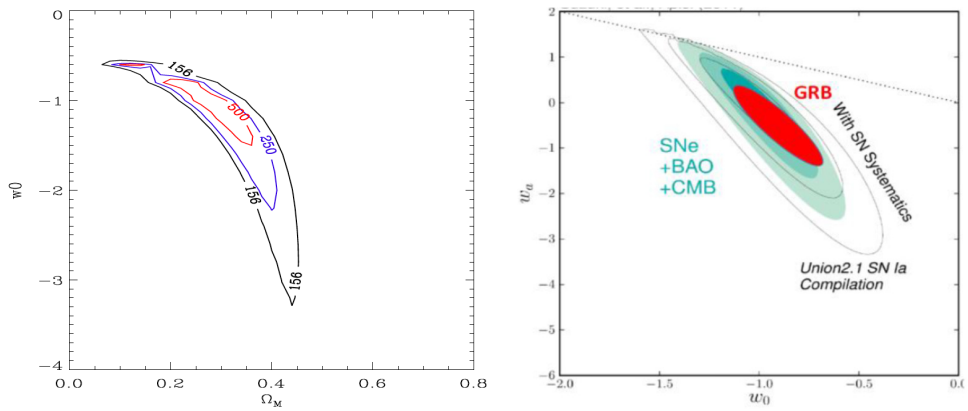


Figure 5 68% confidence level contours in the $\Omega_{\rm M}$–w_0 and w_0–$w_{\rm a}$ planes (by assuming a standard parametrization of the dark energy equation of state: $w = w_0 + w_{\rm a} z/(1+z)$) for a flat FLRW universe derived from the expected future samples by assuming that the the $E_{\rm p,i}$–radiated energy correlation is calibrated with a 10% accuracy by using, e.g., the luminosity distances provided by SNe-Ia, self-calibration or the other methods described in the text (from Amati & Della Valle (2013)).

increase (Ghirlanda et al., 2006).

Understanding the physical basis for the $E_{\rm p,i}$–$E_{\rm iso}$ correlation is also of fundamental importance for both GRB physics and cosmology, and several groups are working on this issue in the framework of the different scenarios that have been proposed for the origin of GRB prompt emission (Zhang & Mészáros, 2002).

6 Summary and conclusions

Given their huge radiated energies and redshift distribution extending from ∼0.01 up to 9.2, GRBs are potentially a very powerful cosmological probe, complementary to other probes (e.g., SNe Ia, galaxy clusters, BAO). As demonstrated by several works, the most promising tool allowing the use of GRBs for measuring cosmological parameters and, in perspective, characterizing the properties of "dark energy" is the correlation between the burst radiated energy $E_{\rm iso}$ and the spectral peak energy $E_{\rm p,i}$. Analyses in the last years provide *independent* evidence that, if we live in a flat universe, then $\Omega_{\rm M}$ is <1 at >99.9% c.l. and around ∼0.3, consistent with current measurements obtained via different methodologies. Further analysis shows that the estimate of $\Omega_{\rm M}$ through the $E_{\rm p,i}$–intensity correlation is robust independently of the choice of luminosity indicator. In particular, $E_{\rm iso}$ appears as the best intensity indicator, especially if computed mono-chromatically at $E_{\rm p,i}$, being also unaffected by the uncertainties in the extrapolation of the spectrum in a broad energy band needed when using "bolometric" quantities. The simultaneous operation of *Swift*, *Fermi*/GBM, Konus-WIND will increase the number of useful samples (z + $E_{\rm p,i}$) at a rate of 15–20 GRB/year, improving the accuracy in the estimate of cosmological parameters. Future GRB experiments (e.g., CALET/GBM, SVOM, Lomonosov/UFFO) will increase dramatically the number of GRB usable in the $E_{\rm p,i}$–$E_{\rm iso}$ plane up to $z \sim 10$ (13.2 Gyrs in terms of look-back time) and allow self-calibration of the correlation. Simulations show that on a time scale of ∼5 years they will be able to measure w_0 and w_a, namely the evolution of dark energy with time, in a complementary way to type Ia SNe.

REFERENCES

Amati, L., Frontera, F., Tavani, M., et al., 2002, A&A, 390, 81
Amati, L., 2006, MNRAS, 372, 233
Amati, L., Guidorzi, C., Frontera, F. et al., 2008, MNRAS, 391, 577
Amati, L., Frontera, F. & Guidorzi, C., 2009, A&A, 508, 173
Amati, L. & Della Valle, M., 2013, IJMPD, 22, 1330028
Capozziello, S. & Izzo, L., 2010, A&A, 519, A73
Capozziello, S., Consiglio, L., De Laurentis, M. et al., ArXiv preprint (2012) 1206.6700
Cardone, V.F., Capozziello, S. & Dainotti, M.G., MNRAS, 400 (2009) 775
Cardone, V.F., Camera, S. & Diaferio, A., JCAP, 2 (2012) 30
Dai, Z.G., Liang, E.W. & Xu, D., 2004, ApJ, 612, L101
Diaferio, A., Ostorero, L. & Cardone, V., JCAP, 10 (2011) 8

Dainotti, M.G., Ostrowski, M. & Willingale, R., MNRAS, 418 (2011) 2202
Demianski, M., Piedipalumbo, E., Rubano, C. & Scodellaro, P., 2008, A&A, 481, 279
Demianski, M., Piedipalumbo, E. & Rubano, C., MNRAS, 411 (2011) 1213
Demianski, M., Piedipalumbo, E., Rubano, C. & Scodellaro, P., MNRAS, 426 (2012) 1396
Freitas, R.C., Goncalves, S.V.B. & Velten, H.E.S., Physics Letters B, 3 (2011) 209
Ghirlanda, G., Ghisellini, G. & Lazzati, D., 2004, ApJ, 616, 331
Ghirlanda, G., Ghisellini, G. & Firmani, C., 2006, New J. Phys., 8, 123
Godet, O., Paul, J., Wei, J.Y., et al., 2012, SPIE Conf. Ser. 8443, p. 1
B. Grossan, I.H. Park, S. Ahmad et al., SPIE Conf. Proc., 8443 (2012) 2
Izzo, L., Muccino, M., Zaninoni, E., Amati, L., Firmani, & Della Valle, M., 2015, A&A, 582, A115
Kodama, Y., Yonetoku, D., Murakami, T. et al., 2008, MNRAS, 391, L1
Lamb, D. Q., Ricker, G. R., Atteia, J.-L. et al., 2004 NewAR, 48, 423
N. Liang, P.-X. Wu, & Z.-H. Zhu, RAA, 11 (2011) 9
J. Lu, Y. Wang, Y. Wu, & T. Wang, EPJC, 71 (2011) 1800
H.J. Mosquera Cuesta, M.H. Dumet M.H. & C. Furlanetto, JCAP, 7 (2008) 4
A. Montiel & N. Bretón, JCAP, 8 (2011) 23
Sari, R., Piran, T. & Halpern, J.P., 1999, ApJ, 519, L17
Sawant, D. & Amati, L., 2015, Proceedings of Swift: 10 Years of Discovery (SWIFT 10), held 2–5 December 2014 at La Sapienza University, Rome, Italy
Schaefer, B.E., 2007, ApJ, 660, 16
P.R. Smale, MNRAS, 418 (2011) 2779
Suzuki, N., Rubin, D., Lidman, C. et al., 2012, ApJ, 746, 85
H. Velten, A. Montiel & S. Carneiro, MNRAS, 431 (2013) 3301
J.-J. Wei, X.-F. Wu & F. Melia, *ApJ* **772** (2013) 43
Yamaoka, K., Yoshida, A., Kotani, T. et al., AIP Conf. Proc., 1133 (2009) 88
Zhang, B. & Mészáros, P., 2002, ApJ, 581, 1236