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Cosmology with gamma-ray bursts

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Gamma-ray bursts constitute one of the most fascinating and relevant phenomena in modern science, with strong implications for several fields of astrophysics, cosmology and fundamental physics. In this short review, I focus on the prospective key-role of GRBs for cosmology. Indeed, the huge luminosity, the redshift distribution extending at least up to $z \sim 10$ and the association with the explosive death of very massive stars make long GRBs (i.e., those lasting up to a few minutes) potentially extremely powerful probes for shedding light on main open issues in our understanding of the early Universe: star formation rate evolution up to the first generation of stars (pop-III), cosmic reionization, luminosity function and metallicity evolution of primordial galaxies up to the "cosmic dawn". At the same time, interesting correlations between luminosity/radiated energy and spectral photon peak energy are the subject of intensive investigations for "standardizing" GRBs and using them for measuring cosmological parameters, investigating the nature and evolution of "dark energy" and testing non-standard cosmological models. I will also report on the status, concepts and expected performances of space mission projects aiming at fully exploiting these potentialities of the GRB phenomenon, thus providing an ideal sinergy with the large e.m. facilities of the future like LSST, ELT, TMT, SKA, CTA, ATHENA.

Keywords: Gamma rays: bursts – cosmology: early Universe – cosmology: cosmological parameters – astronomical instrumentation: future space missions

1 Introduction

Cosmic gamma-ray bursts (GRB) are sudden very bright flashes of X/soft-gamma rays coming at unpredictable times from random directions in the sky and detectable with a rate of $\sim$ one per day by suitable all-sky monitors operating on board satellites in low Earth orbits. After several decades since their discovery in the late 1960s, and thanks to huge observational and theoretical efforts, we know that they come in two main flavours ("long" ones, lasting from a few seconds up to several minutes, and "short" ones, lasting from 1–2 s down to a few tens of ms), that they are followed by a multiwavelength decaying emission called "afterglow", that they are most extreme cosmological phenomena, with a redshift distribution that can reach more than

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9 for long GRBs and isotropic-equivalent radiated energies up to more than 10^{54} erg. Furthermore, there is consolidated evidence that most long GRBs are produced in the core-collapse of massive peculiar stars, whereas most short GRBs should be produced in the very final stages of the merging of NS–NS and NS–BH compact binary systems (that are expected to release also gravitational waves, as demonstrated by the milestone case of GRB 170817A associated to GW 170817). In both cases, the prompt burst of X/gamma-rays is thought to be produced by an ultra-relativistic jet generated and powered by a "central engine" constituted by an accreting black hole or a rapidly spinning and highly magnetized NS produced by the core-collapse of the progenitor star or the NS–NS/NS–BH merger. The multi-wavelength afterglow emission is eventually produced by the shock interaction of the jet with the interstellar medium around the progenitor. See, e.g., Kumar & Zhang (2015) and Pe'er (2015) for reviews of these phenomena.

The unique and exceptional properties summarized above make GRB a phenomenon of paramount importance for several fields of modern astrophysics, extreme and fundamental physics, multi-messenger astrophysics and cosmology (see, e.g., Amati et al., 2008; Amati & Della Valle, 2013; Amati et al., 2018; Ciolfi et al., 2021; Demianski et al., 2021; Stratta et al., 2018; Tanvir et al., 2021). In this short review article, I focus on the latter line of investigation, which is carried on by many research groups worldwide and is the subject of several hundreds of research papers. Particularly relevant and promising is the "use" of long GRB as cosmological probes which comes in two main flavours: investigation of the first billion years ($z > 6$) of the Universe (first population of stars, primordial galaxies, cosmic reionization) and measurement of cosmological parameters (with particular emphasis on the properties and evolution of "dark energy" and, more in general, possible deviation from the standard ΛCDM cosmology).

2 Shedding light on the early Universe with GRBs

A major goal of contemporary astrophysics and cosmology is to achieve a detailed understanding of the formation of the first collapsed structures, the nature of the first generation of stars (Population III), the reionization of the intergalactic medium (IGM), and the build-up of heavy atoms during the first billion years of the Universe. GRBs and their faint host galaxies can be found at very high redshifts and provide multiple powerful probes of early star formation, metal-enrichment and galaxy evolution, and the reionization history of the IGM.

GRBs are detectable independently of the luminosity of their underlying host galaxy and can provide detection and characterization of very low-mass/low-luminosity primordial galaxies below the detection limits even of facilities such as JWST and the future ELTs. Their luminous afterglows act as beacons with which we can probe the IGM and interstellar medium (ISM) in absorption in these very faint galaxies (e.g., Tanvir et al., 2021).

2.1 Unveiling and characterizing the bulk of primordial "invisible" galaxies

Long-duration GRBs are produced by massive stars, and so track star formation, and in particular the populations of UV-bright stars responsible for the bulk of ionizing radiation production. This makes them powerful probes of global star formation and changes in the initial mass function (IMF). However, the intrinsically very faint galaxies, which appear to increasingly dominate star formation at $z > 3$, are very hard to detect directly at $z > 6$ even with JWST. GRBs circumvent this difficulty, sign-posting the existence and redshifts of their host galaxies, no matter how faint. Analyses of GRB locations have confirmed that the majority of star formation at $z > 6$ occurred in galaxies below the effective detection limit of HST with expected magnitudes fainter than mAB $\sim$ 30, at the limit of what is reachable with JWST and the ELTs.

The deepest galaxy surveys carried out by the HST has revealed that the faint end of the luminosity function (LF) steepens significantly with redshift reaching a power-law of slope $\alpha \sim 2$ at $z > 6$. Analyses of the SFR densities from GRB tracers compared to UV galaxy surveys have indicated discrepant results, suggesting an extremely steep faint-end slope of the galaxy LF at $z > 6$, that must continue to very faint magnitudes (e.g. MUV > –11). Even in the JWST era, the numerous galaxies populating the faint-end of the LF (MUV > –16 mag) will be mostly out of reach. Alternatively, the stellar IMF may become more top-heavy, providing consistency with GRB counts and indeed enhancing their contribution to reionization. For such faint galaxies, bright GRB afterglows provide ideal backlights for measuring not only the atomic hydrogen column, but also obtaining exquisite measurements of abundances and gas kinematics probing to the hearts of their host galaxies. Thus, GRBs can be used to monitor cosmic metal enrichment and chemical evolution to early times, and search for evidence of the nucleosynthetic products of even earlier generations of stars. Using a sample of $\sim$50 high-z GRBs to trace the ISM in galaxies at $z > 6$ will be the only way to map robust metallicities and abundance patterns across the entire population of star-forming galaxies, in particular allowing for the analysis of the chemical enrichment signatures in very faint galaxies in the early Universe.

2.2 Unveiling and characterizing the pop-III stars population

High-redshift GRBs provide several routes for exploring the earliest populations of metal-free and ultra-low metallicity stars from direct spectroscopic measurements of ISM abundances, and changes in the numbers and properties of the bursts themselves. The low-opacity envelope in massive population III stars combined with limited mass loss favor conditions for very energetic GRBs and models predict that they are several orders of magnitude more energetic than GRBs from population I/II progenitors.

Spectroscopy of afterglows obtained by 30–40 m-class ELTs may reveal ultra-low metallicities and would represent direct evidence for the association between a GRB and a Pop-III star progenitor. Abundance patterns reveal if the first heavy elements were produced by typical core-collapse explosions or by other mechanisms such as pair-instability supernovae, hence constraining the IMF up to the earliest cosmic epochs. Pop-III stars are likely to have played a major role in the growth of

the very first bound structures in early cosmic times, through chemical feedback and metal enrichment of the primordial IGM, and they may have also contributed a head start to the cosmic reionization process. Even a single GRB unveiling a Pop-III star progenitor or a Pop-III star enriched medium would put fundamental constraints on the unknown properties of the first stars and represent a major breakthrough in our understanding of first-light sources.

2.3 Star formation rate evolution and cosmic reionization

The evolution of the IGM from a completely neutral to a fully ionized state is intimately linked to early structure formation, and is thus a central issue for cosmology. Answering the key question hinges on two issues: How much massive star formation was occurring as a function of redshift, and what average proportion of the ionizing radiation produced by these massive stars escaped from the immediate environs of their host galaxies. Even in the JWST/ELT era, direct observations of escaping Lyman-continuum radiation at $z > 5$ will remain unfeasible due to the absorption of the IGM Ly-α forest. Moreover, current GRB measurements that only have been possible at $z = 2$–6 indicate a strong upper limit of <2%, far below the escape-fraction needed for reionization.

The former question about massive star formation as a function of redshift can be extrapolated based on galaxy LFs. However, two very significant uncertainties are, firstly, the completeness and accuracy of the photometric redshift samples at $z > 7$, and, secondly, the poorly constrained faint-end behavior of the galaxy LF at stellar masses $< \sim 10^8\ M_\odot$, especially since galaxies below the HST and potentially below the JWST detection limit, even through cluster-lens observations, very likely dominate the star-formation budget. The second question on the Ly-continuum escape-fraction is even more difficult since it cannot be determined directly at these redshifts. Recent stacked spectroscopic analyses of lower-redshift galaxies have suggested escape fractions as high as 10%, which could be sufficient to drive reionization, but it is unclear whether the galaxy samples at $z \sim 3$ used to measure the escape fractions are representative of all star-forming galaxies, and in particularly of the typical, intrinsically fainter galaxies at $z > 7$.

Observations of >40 z >6 GRBs with both on-board spectroscopy and with 30–40-m class ground-based telescope follow-up observations will provide accurate constraints on the product of the UV luminosity density ρ_{UV} and average escape fraction, f_{esc}, along the line of sight to massive stars in galaxies during the epoch of reionization. This will allow us to confidently distinguish between conventional models in which starlight brings about reionization, and models that fail (e.g. if the escape fraction remains as low as a few percent).

Finally, it is expected that reionization should proceed in a patchy way, for example, ionized bubbles may form first around the highest density peaks, where the first galaxies form, expanding and ultimately filling the whole IGM. The topology of the growing network of ionized regions reflects the character of the early structure formation and the ionizing radiation field. Forthcoming SKA 21cm observations will reveal the topology of reionization through 3-dimensional mapping of ionized halos at $z \sim 7$–20, while GRB afterglows pinpoint the exact locations and nature of the ionizing sources. With samples of >40 GRBs at $z > 6$–10, combined with ground-

based high spectral resolution follow-up observations by the ELTs, we can investigate statistically the redshift dependence of the average and variance of the reionization process, with a particular focus on the environments of less massive galaxies, that may dominate the number densities and be the drivers of the reionization.

3 Measuring cosmological parameters with GRBs

GRBs are the brightest cosmological sources in the Universe, and detectable up to the first hundred millions years after the Big Bang thanks to the enormous energy that they release in the X/gamma-rays (the isotropic radiated energy, $E_{\rm iso}$, can reach $\simeq 10^{54}$ erg released typically in a few tens or hundreds of seconds). Their redshift distribution extends from 0.0085 (GRB 980425) up to $\sim$ 9.4 (GRB 090429B). In addition, they emit most of their radiation in hard X-rays, so that they do not suffer from dust absorption. These phenomena are not standard candles, given that their total radiated energies or peak luminosities span several orders of magnitude, but the discovery and intensive study of empirical correlations between distance-dependent quantities and rest-frame observables has opened to us the possibility of standardizing these sources as cosmological probes, and extend the Hubble diagram in a previously unexplored range of redshift (Amati et al., 2002, 2008; Amati & Della Valle, 2013; Dainotti & Amati, 2018; Demianski et al., 2021; Izzo et al., 2015). The use of GRBs for cosmology through the $E_{\rm p,i}$–$E_{\rm iso}$ ("Amati") relation and other correlations involving radiated energy or luminosity of the prompt and/or afterglow emission has been the subject of tough investigation by many research groups worldwide since more than one decade ago (Amati et al., 2002, 2008; Amati & Della Valle, 2013). The main power of GRBs as cosmological probes lies in their huge brightness in the X- and soft gamma-rays domain, which makes them detectable up to redshift 10 or more, combined to the huge follow-up efforts in the optical/NIR follow-up, allowing the redshift measurement. This allows us to extend the Hubble diagram substantially beyond the redshift range of Type-Ia SNe and even BAO, in a regime where only high-z AGNs can partly compete. As demonstrated by analysis and simulations, this redshift extension is fundamental for testing DE models and, more in general, cosmological scenarios alternative to the standard ΛCDM.

3.1 Independent estimates of cosmological parameters through the $E_{\rm p,i}$–$E_{\rm iso}$ correlation

GRBs show non thermal spectra which can be empirically modeled with the Band function, which is a smoothly broken power law with parameters α, the low-energy spectral index, β, the high energy spectral index and the *roll-over* energy E_0.

Given that β is almost always found to be <-2, GRB νFν spectra show a peak corresponding to a value of the photon energy $E_{\rm p} = E_0(2+\alpha)$, ranging typically from $\sim$5–10 up to 1000–5000 keV. For those GRBs with well measured prompt emission spectrum and redshift, it is possible to evaluate the "intrinsic" (i.e., in the cosmological rest-frame) peak energy, $E_{\rm p,i} = E_{\rm p}(1+z)$ and the isotropic-equivalent radiated energy, defined as:

$$E_{\rm iso} = 4\pi D_{\rm L}^2(z,\theta)\,(1+z)^{-1}\int_{1/(1+z)}^{10^4/(1+z)} EN(E)dE\,. \quad (1)$$

The quantity $E_{\rm iso}$ spans several orders of magnitude, typically ranging from 10^{50} to 10^{54} erg. It is important to note that, while there are observational and theoretical evidences suggesting that the GRB emission is collimated within a few tens of degrees or less, we are still lacking a firm and reliable method for estimating the jet opening angle of single GRBs. This is why, conservatively, $E_{\rm iso}$, or the isotropic-equivalent peak luminosity, $L_{\rm iso}$, are still used as indicators of the GRB "brightness".

The existence of a strong correlation between $E_{\rm p,i}$ and $E_{\rm iso}$ of long GRBs was inferred more than 20 years ago based on the systematic analysis of GRB spectra and fluences, and was actually discovered in 2002 based on the first sample of BepppoSAX GRBs with measured redshift (Amati et al., 2002). The $E_{\rm p,i}$–$E_{\rm iso}$ ("Amati") correlation was then confirmed by later measurements by several different GRB detectors (Amati et al., 2008; Amati & Della Valle, 2013; Dainotti & Amati, 2018) and can be modeled as a linear relation between the logarithms of the two quantities:

$$\log\left[\frac{E_{\rm p,i}}{\rm keV}\right] = b + a\log\left[\frac{E_{\rm iso}}{10^{52}\ {\rm erg}}\right]. \quad (2)$$

The $E_{\rm p,i}$–$E_{\rm iso}$ correlation is characterized by an intrinsic additional extra-Poissonian scatter, σ_{int}, around the best-fit line that has to be taken into account and determined together with (a,b) by the fitting procedure. According to this method the data (x_i,y_i) are correlated by a linear function $y=ax+b$ with the addition of an extrinsic scatter σ_{int}, and the best fit value of the parameters (a,b and σ_{int}) are obtained by minimizing the -log (likelihood) function, in which the uncertainties $\sigma_{x,i}$ and $\sigma_{y,i}$ on both (x_i,y_i) are taken into account.

The values of the normalization, slope and intrinsic dispersion of the $E_{\rm p,i}$–$E_{\rm iso}$ correlation in the logarithmic form are found to be $\sim$2, $\sim$0.5 and $\sim$0.2 dex, respectively, with slight variations depending on the sub-sample considered.

The existence and properties of this correlation have been widely investigated by many research groups in the last twenty years, because of its key role for understanding the GRB prompt emission physics, jet structure and geometry and viewing angle effects, as well as for the identification and nature of different sub-classes of these events, such as: short vs. long, X-ray flashes and under-luminous GRBs, ultra-long GRBs, etc.

The "Amati" relation becomes a distance indicator through the measurement of $E_{\rm iso}$ that is derived from the observed fluence, which in turn depends on the geometry and expansion rate of our Universe through the so-called luminosity distance. Unlike historical "standardized" candles as SNe Ia that can be calibrated via Cepheids, we don't have a statistically significant sample of GRBs at low redshift which allows us to determine the parameters of the correlation in a cosmology-independent way. Which means that the existence and properties of the correlation were found by assuming a fiducial cosmological model. Thus, if we wish to use it for measuring cosmological parameters we are obviously affected by a circularity problem. The most straightforward way to get rid of it is to simultaneously constrain the calibration parameters (a,b,σ_{int}) and the set of cosmological parameters by considering a chosen likelihood

function. In practice, this task consists in determining the multi-dimensional probability distribution function (PDF) of the parameters $\{a, b, \sigma_{\rm int}, \mathbf{p}\}$, where $\mathbf{p}$ is the N-dimensional vector of the cosmological parameters.

This is the method adopted by (Amati et al., 2008) in the first work aimed at verifying if the $E_{\rm p,i}$–$E_{\rm iso}$ correlation could actually be used for cosmology. By assuming a flat ΛCDM cosmology it was found that, actually, the goodness of fit of the correlation varied as a function of $\Omega_{\rm m}$ following a nice parabolic shape with a minimum at about 0.2–0.3. The analysis performed on larger samples in the following years made this result more and more reliable and accurate, showing that GRBs provide – in the framework of ΛCDM cosmology – a firm and independent evidence for the case of an accelerating Universe with $\Omega_{\rm m} \sim 0.3$. This result is further confirmed by releasing the flat universe assumption, i.e., by letting both $\Omega_{\rm m}$ and Ω_Λ free to vary (see next sections).

3.2 Calibrating the $E_{\rm p,i}$–$E_{\rm iso}$ correlation with SNe Ia and other probes

In addition to the clean and independent approach described above, different and alternative techniques for getting rid of the circularity issue when using the $E_{\rm p,i}$–$E_{\rm iso}$ ($L_{\rm iso}$) correlation for cosmology have been developed and presented in the literature.

As anticipated, most of these methods use SNe Ia for calibrating the correlation for those GRBs at redshift lower than about 1.5 using the luminosity distances derived from SNe Ia (e.g., Demianski et al., 2021). It is worth pointing out that the use of GRBs as distance indicators has an advantage over SNe Ia: they can explore a broader range of redshifts, extending to $z \sim 10$ instead of $z \sim 2$. However, if we calibrate the GRBs with SNe Ia, the GRBs are no longer independent distance indicators. In the "distance scale" jargon, the GRBs have become "tertiary" indicators because in turn the SNe Ia are calibrated with the Cepheids. This is a different approach from that described in previous section, where GRBs remain independent cosmological probes. The typical regression procedure adopted in these approaches can be schematically sketched as follows: set the redshift range where the modulus of distance, $\mu(z)$, has to be reconstructed; sort the SNe Ia sample by increasing value of $|z - z_i|$ and select the first $n = \alpha N_{\rm SNe\,Ia}$, where α is a user-selected value and $N_{\rm SNe\,Ia}$ the total number of SNe Ia; apply the weight function

$$W(u) = \begin{cases} (1 - |u|^2)^2 & |u| \leq 1 \\ \\ 0 & |u| \geq 1 \end{cases} , \tag{3}$$

where $u = |z - z_i|/\Delta$ and Δ is the highest value of the $|z - z_i|$ over the previously selected subset; fit a first-order polynomial to the data previously selected and weighted, and use the zeroth-order term as the best-fit value of the modulus of distance $\mu(z)$; evaluate the error σ_μ as the root mean square of the weighted residuals with respect to the best-fit value.

Finally, the reconstructed $\mu(z)$ can be used to obtain the luminosity distance, and fit the $E_{\rm p,i}$–$E_{\rm iso}$ correlation relation (i.e. determine the parameters (a, b, σ_{int})) as expressed by Eq. 2, without assuming any particular cosmological model. Only GRBs with $z \leq 1.414$ are considered, in order to cover the same redshift range spanned by

the SNe Ia data. The radiated energy $E_{\rm iso}$ of each burst at high redshift can then be derived through the calibrated $E_{\rm p,i}$–$E_{\rm iso}$ correlation, thus allowing us to finally obtain the luminosity distance, $D_{\rm L}(z)$, and construct the GRB Hubble diagram:

$$D_{\rm L}(z) = \left(\frac{E_{\rm iso}(1+z)}{4\pi S_{bolo}} \right)^{1/2} . \tag{4}$$

The uncertainty of $D_L(z)$ can be estimated through the propagation of the measurement errors of the pertinent quantities. It turns out that

$$5 \log D_L(z) = \left(\frac{5}{2} \right) \left\{ b + a \log \left[\frac{E_{\rm p,i}}{300 \text{ keV}} \right] - \log \left(4\pi S_{bolo} \right) + \mu_0 \right\}, \tag{5}$$

where μ_0 is a normalization parameter, due to the fact that the distance moduli of GRBs are not absolute; thus, this cross-calibration parameter is needed to match the GRB Hubble diagram and the one of SNe Ia.

Other approaches have been presented in literature, which exploit different interpolation of the luminosity distance and employ different data samples at intermediate redshifts including BAO datasets. As anticipated, it turns out that the price of applying all these calibration techniques is that GRBs are a cosmological probe not fully independent. On the other hand, if we simultaneously constrain the calibration parameters (a, b, σ_{int}) and the set of cosmological parameters, it turns out that the parameters of the correlations depend on the cosmological model and are coupled to the cosmological parameters. When future GRB missions will substantially increase the number of GRBs available to construct the $E_{\rm p,i}$–$E_{\rm iso}$ correlation, they may shed new light on the properties of this important correlation.

3.3 Use of correlations involving also X-ray afterglow properties

As discussed at the beginning of this section, the quest for correlations between GRB properties, is aimed at shedding light on the emission processes and at enabling the use of these phenomena for measuring cosmological parameters, involved not only the X/gamma-ray prompt phase but also the early X-ray afterglow emission (Dainotti & Amati, 2018; Dainotti et al., 2022; Izzo et al., 2015; Muccino et al., 2021). Among these, the most investigated are those involving the duration of the "plateau" phase, T_a and the luminosity at the end of this phase, usually referred to as L_X (Dainotti & Amati, 2018; Dainotti et al., 2022). Indeed, as shown and discussed by several authors, there exists a significant correlation between these two quantities, as well as a 3D correlation obtained by including the peak luminosity of the prompt emission, L_p. In particular, it has been found that these correlations become tight for sub-samples selected based on other characteristics, including the nature of the progenitor and multi-wavelength properties. This method, while still affected by the relatively low number of events that can be used for each sub-sample and sample selection effects, seems promising for the purpose of GRB cosmology, especially in view of the wealth of new data on GRB prompt and afterglow emission expected in the near future thanks to the continuing operation of Swift, Fermi, Konus-WIND and other GRB experiments, as well as increased efficiency of follow-up with ground facilities.

An important step forward in this line of investigation may be provided by the use of the "Combo" relation, which extends the "Amati" relation through the inclusion of X-ray afterglow observables like the initial luminosity, the rest-frame duration of the shallow phase, and the index of the late power-law decay, combined with an innovative calibration method minimizing the dependence on the systematics possibly affecting SNe Ia. The main novelty provided with the Combo relation consists in the afterglow X-ray light-curve fitting procedure through a piece-wise function that is capable to model the very early power-law decay and the following "plateau" emission, getting rid of X-ray flaring emission over-imposed to the underlying afterglow behavior. This procedure, similar to the analysis currently developed for SNe Ia, allows us to measure with great accuracy the main observables of the Combo relation: indeed, among the entire sample of Swift long GRBs showing a complete light curve in X-ray, and characterized by a known peak energy of the corresponding prompt emission, no outliers have been found so far.

In a preliminary analysis on a sample of 60 GRBs with well measured parameters of both prompt and early X-ray afterglow emission, Izzo et al. (2015) showed that actually the Combo relation could provide a value of $\Omega_{\rm m}= 0.29^{+0.23}_{-0.15}$. By applying the Combo relation to an updated sample of 174 gamma-ray bursts, Muccino et al. (2021) could obtain tighter bounds on $\Omega_{\rm m}$, and investigate the possible evidence of evolving dark energy parameter $w(z)$. The $w(z)$ evolution was studied by binning the GRB Hubble diagram in seven redshift intervals and assuming two priors over the Hubble constant in tension at 4.4σ, i.e., $H_0 = (67.4 \pm 0.5)$ km s^{-1}Mpc^{-1}and $H_0 = (74.03 \pm 1.42)$ km s^{-1}Mpc^{-1}. It was found that at $z \leq 1.2$ $w(z)$ agrees within 1σ with the standard value $w = -1$, whereas at larger z the $w(z)$ estimated from GRBs seem to deviate from $w = -1$ at 2σ and 4σ level, depending on the redshift bins. These results indicate that the dark energy equation of state parameter can be different from the ΛCDM value $w = -1$ at larger z, although its contribution to the energy budget of the Universe is still negligible, and also confirm the Combo relation as a powerful tool to investigate cosmological evolution of dark energy.

4 Multi-messenger cosmology with short GRBs

The detection of short GRB 170817A is temporal and spatial coincidence with the gravitational-wave (GW) signal GW 170817A detected by LIGO and Virgo marked the birth of multi-messenger astrophysics and beautifully demonstrated the hypothesis that compact binaries (NS–NS, NS–BH) coalescence (CBC) produce both GW and gamma-ray burst emissions, as well as near-infrared emission (kilonova, KN) emitted by the radioactive decay of heavy elements being formed in the after-merging phase. In addition to the unique insights on the fundamental physics of neutron stars, black holes, relativistic jets, formation of heavy elements, getting a sample of even a few tens of such simultaneous short GRB–GW detections would allow us to enhance substantially the potentiality of GW astrophysics for measuring cosmological parameters (see, e.g., Stratta et al., 2018; Ciolfi et al., 2021; Maggiore et al., 2020).

Independent measurements of the Hubble constant H_0 are of utmost importance in order to understand if the current tension is due to possible systematics or is the sign of a cosmological crisis that requires new paradigms. The detection of GWs from CBCs

and the measurement of their redshift through their electromagnetic counterparts has already been proven to be a new probe for H_0 in the case of GW170817. To solve the current tension, a precision level at least of the order of ∼1% should be reached and a large number of CBCs with measured redshift are needed. In this context, observations of a large number of short GRBs in synergy with GW interferometers represents a unique opportunity. Simulations of NS–NS mergers observed with the 3G network along with an instrument like THESEUS/XGIS predict a number of joint detections of ∼130–200 in ten years, from which H_0 can be measured with a precision of 0.2%–0.4% by assuming that a redshift can be measured for all events via either optical or X-ray spectroscopy (Maggiore et al., 2020; Ciolfi et al., 2021). With this assumption, simulations show that, by rescaling these precision levels as $1/\sqrt{N}$, the goal of $\Delta H_0 \ / H_0 \sim 1\%$ can be reached with $N \sim 15$ events jointly observed with the 3G network (ET+CE+CE) and $N \sim 25$ events jointly observed with ET only (the lower number of events providing $\Delta H_0 \ // H_0 \sim 1\%$ with the ET+CE+CE network with respect to ET only is due to the better parameter estimation with the former network).

In the late '30s, the simultaneous GW + e.m. counterpart detection, and hence redshift measurement, for a few tens of CBC events will also allow us to extend multi-messenger cosmology beyond the investigation of H_0. Indeed, a much higher potential for discovery is provided by the fact that ET will have access to standard sirens at much larger redshifts, where effects genuinely induced by a non-trivial dark energy sector and by modifications of General Relativity on cosmological scales become accessible. First of all, away from the current limit $z \ll 1$, the effect of the dark energy density becomes significant in the Hubble diagram, which would allow us to obtain a measurement of the dark energy equation of state from GW observations. In addition, the situation for 3G GW detectors is even more interesting due to a phenomenon of modified GW propagation. Indeed, a natural theoretical framework for having a dark energy sector different from a simple cosmological constant is provided by modifications of GR at the cosmological scale (Maggiore et al., 2020).

5 GRB cosmology with next generation space missions

The continuing operation of current main GRB missions and instruments (e.g., Swift, Fermi/GBM, Konus-WIND, AGILE), the follow-up efforts with ground small robotic and larger optical/NIR facilities, as well as the coming into play of new space missions like SVOM and Einstein probe (EP) will grant in the next years of this decade a significant step forward in the assessment and use of GRBs for the cosmological investigations outlined in previous sections. But really a breakthrough advancement of this fields of research is expected with the next generation GRB and high-energy transients mission, which are being designed by large international collaborations for fully exploiting the great potentialities of GRBs for cosmology and multi-messenger astrophysics (e.g., THESEUS, Gamow Explorer, HiZ-Gundam). Most of these mission concepts aim at improving substantially the capability of detecting, identifying and characterizing high-z GRBs, and, more in general, all classes of GRBs, by extending down to the soft X-rays, with deep sensitivity, the GRB monitoring and carrying on-board the prompt NIR follow-up capabilities, arcsec transient localization and red-

shift measurement. Among these mission concepts, the Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is the most advanced one (Amati et al., 2018; Stratta et al., 2018).

Developed by a large international collaboration, in 2018 THESEUS was selected by ESA for a three years Phase 0/A study as one of the three candidates for the M5 medium-class space mission opportunity, for a launch in ∼2032. The scientific goals for the exploration of the early Universe require the detection, identification, and characterization of several tens of long GRBs which occurred in the first billion years of the Universe ($z > 6$) within the 4 years of nominal mission lifetime of THESEUS. This would be a giant leap with respect to what has been obtained in the last 20 years (7 GRBs at >6), using past and current GRB dedicated experiments like Swift/BAT, Fermi/GBM, Konus-WIND combined with intensive follow-up programs from the ground with small robotic and large telescopes (e.g., VLT). This breakthrough performance can be achieved by overcoming the current limitations through an extension of the GRB monitoring passband to the soft X-rays with an increase of at least one order of magnitude in sensitivity with respect to previously flown wide-field X-ray monitors, as well as a substantial improvement of the efficiency of counterpart detection, spectroscopy and redshift measurement through prompt on-board NIR follow-up observations. At the same time, the objectives on multi-messenger astrophysics and, more generally, time domain astronomy, require: a) a substantial advancement in the detection and localization, over a large (>2 sr) Field-of-View (FoV) of short GRBs as electromagnetic counterparts of GW signals coming from NS-NS, and possibly NS-BH) mergers; b) monitoring the high-energy sky with an unprecedented combination of sensitivity, location accuracy and field of view in the soft X-rays; c) imaging up to the hard X-rays and spectroscopy / timing to the soft gamma-rays. Based on these mission scientific requirements and the unique heritage and Consortium worldwide leadership in the enabling technologies, the THESEUS payload would include the following scientific instruments.

- Soft X-ray Imager (SXI, 0.3–5 keV): a set of two "Lobster-eye" telescope units, covering a total FoV of 0.5 sr with source location accuracy $< 2'$, focusing onto innovative large size X-ray CMOS detectors.
- X-Gamma-ray Imaging Spectrometer (XGIS, 2 keV–10 MeV): a set of two coded-mask cameras using monolithic SDD+CsI X- and gamma-ray detectors, granting a ∼2 sr imaging FoV and a source location accuracy <15 arcmin in 2–150 keV, an energy band from 2 keV up to 10 MeV and few μs timing resolution.
- InfraRed Telescope (IRT, 0.7–1.8 μ): a 0.7 m class IR telescope with $15' \times 15'$ FoV, with imaging (I, Z, Y, J and H) and moderate spectroscopic (resolving power, R 400, through $2' \times 2'$ grism) capabilities.

The baseline launcher/orbit configuration is a launch with Vega-C to a low inclination ($< 6°$) Low Earth Orbit (LEO, 550–640 km altitude), which has the unique advantages of granting a low and stable background level in the high-energy instruments, allowing the exploitation of the Earth's magnetic field for spacecraft fast slewing and facilitating the prompt transmission of transient triggers and positions to the ground. The mission profile will include a spacecraft autonomous slewing capability >7°/min, so to allow fast NIR follow-up with the IRT of GRBs and transients detected and

localized by the monitors (SXI and XGIS). Through the Lyman-alpha spectral break between photometric bands, THESEUS IRT will perform on-board photometric redshift determination better than 10%, while the IRT spectrum will identify absorption features, and provide constraints within ∼0.2 dex on the hydrogen column density along the GRB line of sight. The identification of metal absorption lines will also refine spectroscopic redshift determinations to a precision of <1%.

As demonstrated by intensive simulations performed by ESA and the THESEUS consortium, during its scientific operation time, THESEUS will locate and identify >40 GRBs at $z > 6$ through direct on-board follow-up at optical to near-IR wavelengths with the IRT. THESEUS will be able to detect such very high-redshift GRBs, rapidly identifying and characterizing on-board the highest redshifts events and transmitting the corresponding information to ground within 1 hour of the GRB detection. This guarantees great synergies with extremely sensitive facilities as JWST (expected to be operative at the end of the 2030s) and ELTs, which will be eventually following-up these unprecedented targets for the exploration of the early Universe. In comparison to THESEUS, the upcoming GRB mission SVOM is expected to have a rate of detection of the highest redshift GRBs similar to Swift, but as with Swift, it too lacks on-board infrared detection capability to provide indication of very high redshift origin. The Einstein Probe (the other X-ray mission scheduled for launch in the near future) has neither the high energy sensitivity to confirm sources as GRBs, nor optical or infrared capabilities. Thus, the sample of high-z GRBs will only increase slowly without a more powerful mission. THESEUS will be well aligned with the advent of ground-based 30–40 m class telescopes for additional, very deep spectroscopic follow-up.

On the multi-messenger astrophysics and cosmology side, ESA and THESEUS consortium simulations show that, during its nominal mission lifetime, THESEUS/XGIS and SXI are expected to detect and accurately (<15 arcmin for 90% and <7 arcmin for 50%) localize ∼40 short GRBs (∼12/yr assuming 3.45 years of observations) inside their imaging field of view. This number is based on a population synthesis model of short GRBs normalized to past Fermi and Swift observations and takes into account all payload observational constraints (Amati et al., 2018; Tanvir et al., 2021). In addition, ∼28/yr short GRBs at higher energies (>150 keV) will be detected outside the XGIS imaging field of view, with coarse sky localization (∼500 deg^2) yet enough to establish, together with the temporal coincidence, an association with a GW event. Based on state-of-the-art GRB jet structure modeling, the number of NS–NS mergers detected with the 3G GW network and, at the same time, by THESEUS/XGIS+SXI in survey mode has been estimated by considering a variety of high-energy EM signals expected from NS–NS mergers, employing for the latter a population synthesis model normalized to current Fermi short GRB catalog. The different high-energy signals include (i) the prompt short GRB emission, observable within a few degrees from the jet propagation axis (the only component considered in previous published estimates; (ii) the standard afterglow emission in the X-ray band from the forward shock of the jet propagating across the interstellar medium, and (iii) the X-ray high-latitude emission (HLE) from the prompt short GRB phase, which also represents a promising explanation for the observed X-ray plateaus often accompanying short GRBs. Two scenarios for the 3G interferometers have been considered: 1) ET alone, 2) ET plus 2 CE, one located in the LIGO-Livingston site (US) and the other one in Australia. A

large number of joint detections are expected (∼70 and ∼90, respectively, in only 3.5 years of operations), showing that THESEUS will allow for the first statistical studies on multi-messenger NS–NS (and possibly NS–BH) merger events (Stratta et al., 2018; Ciolfi et al., 2021).

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