Cosmology with Gamma-Ray Bursts: status and perspectives

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First National Meeting on Science and Technology with SKA
The Italian pathway to SKA
Why looking for more cosmological probes?

- different distribution in redshift -> different sensitivity to different cosmological parameters

\[ D_L = \frac{(1 + z)c}{H_o} \left| k \right|^{0.5} \times S \left\{ k \right|^{0.5} \int_0^z [k(1 + z)^2 + \Omega_M (1 + z')^3 + \Omega_\Lambda]^{-0.5} dz' \]
Recent results from SNLS (231 SNe Ia at $0.15 < z < 1.1$, Guy et al. 2010) compared to those of Astier et al. 2006 (44 low redshift SNe along with the 71 SNe from the SNLS first year sample)
Each cosmological probe is characterized by possible systematics

- e.g. SN Ia:
  - different explosion mechanism and progenitor systems? May depend on z?
  - light curve shape correction for the luminosity normalisation may depend on z
  - signatures of evolution in the colours
  - correction for dust extinction
  - anomalous luminosity-color relation
  - contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)
If the “offset from the truth” is just 0.1 mag....

(slide by M. della Valle)
Are GRB standard candles?

- all GRBs with measured redshift (~250, including a few short GRBs) lie at cosmological distances ($z = 0.033 \text{ to } \sim 9.4$) (except for the peculiar GRB980425, $z=0.0085$)

- isotropic luminosities and radiated energy are huge and span several orders of magnitude: GRB are not standard candles (unfortunately)

Jakobsson, 2009

Amati, 2009
* jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, are of the order of few degrees

* the collimation-corrected radiated energy spans the range $\sim 5 \times 10^{49} - 5 \times 10^{52}$ erg -> more clustered but still not standard

\[ \theta = 0.09 \left( \frac{t_{jet,d}}{1 + z} \right)^{3/8} \left( \frac{n_\gamma \eta_\gamma}{E_{\gamma,iso,52}} \right)^{1/8} \]

\[ E_\gamma = (1 - \cos \theta) E_{\gamma,iso} \]

Ghirlanda et al., 2004
- GRBs have huge luminosity, a redshift distribution extending far beyond SN Ia.
- High energy emission -> no extinction problems.

Ghirlanda et al, 2006
- GRB have huge luminosity, a redshift distribution extending far beyond SN Ia
- high energy emission -> no extinction problems
- potentially powerful cosmological sources but need to investigate their properties to find ways to standardize them (if possible)

Ghirlanda et al, 2006
The $E_{p,i} - E_{iso}$ correlation

- GRB spectra typically described by the empirical Band function with parameters
  $\alpha = $ low-energy index, $\beta = $ high-energy index, $E_0 = $ break energy

- $E_p = E_0 \times (2 + \alpha) = $ observed peak energy of the $\nu F_{\nu}$ spectrum

- measured spectrum + measured redshift -> intrinsic peak energy and radiated energy

$$E_{p,i} = E_p \times (1 + z)$$

$E_{\gamma,iso} = \frac{4\pi D_i^2}{(1+z)} \int_{1/(1+z)}^{10^4/(1+z)} E \, N(E) \, dE \, \text{erg}$

Jakobsson (2009)
~260 GRBs with measured redshift, about 50% have measured spectra

both $E_p$, $i$ and $E_{iso}$ span several orders of magnitude and a distribution which can be described by a Gaussian plus a low – energy tail (“intrinsic” XRFs and sub-energetic events)

Amati et al. (A&A 2002): significant correlation between $E_{p,i}$ and $E_{iso}$ found based on a small sample of BeppoSAX GRBs with known redshift.
Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities

130 long GRBs as of Sept. 2011

BeppoSAX GRBs
Swift: reduction of selection effects in redshift

Ep,i of Swift GRBs measured by Konus-WIND, Suzaku/WAM, Fermi/GBM and BAT (values provided by the Swift/BAT team (GCNs or Sakamoto et al. 2008).
Fermi: unprecedented broad-band coverage of prompt emission (∼10 keV – GeV) – reduction of biases in measurement of Ep

When computing Ep,i and Eiso based on the fit with Band function (unless CPL significantly better) all Fermi/GBM long GRBs with known z are fully consistent with Ep,i – Eiso correlation as determined with previous / other experiments, both when considering preliminary fits (GCNs) or refined analysis (e.g., Nava et al. 2011)

Amati 2012

Zhang et al. 2012
- the correlation holds also when substituting $E_{\text{iso}}$ with $L_{\text{iso}}$ (e.g., Lamb et al. 2004) or $L_{\text{peak,iso}}$ (Yonetoku et al. 2004, Ghirlanda et al., 2005)
- this is expected because $L_{\text{iso}}$ and $L_{\text{peak,iso}}$ are strongly correlated with $E_{\text{iso}}$
- w.r.t. to $E_{\text{iso}}$, $L_{\text{iso}}$ and $L_{\text{p,iso}}$ are more difficult to estimate and subject to larger uncertainties
the $E_p,i-\text{Liso}$ correlation holds also within a good fraction of GRBs (Liang et al. 2004, Firmani et al. 2008, Frontera et al. 2012, Ghirlanda et al. 2009): robust evidence for a physical origin and clues to explanation


Fermi (e.g., Li et al., ApJ, 2012)
No evidence of evolution of index and normalization of the $E_{p,i} - E_{iso}$ correlation with redshift.
- strong correlation but significant dispersion of the data around the best-fit power-law; the distribution of the residuals can be fit with a Gaussian with $\sigma(\log E_{p,i}) \sim 0.2$

- the "extra-statistical scatter" of the data can be quantified by performing a fit with a maximum likelihood method (D’Agostini 2005) which accounts for sample variance and the uncertainties on both X and Y quantities

$$L(m, c, \sigma_v; x, y) = \frac{1}{2} \sum_i \log (\sigma_v^2 + \sigma_y^2 + m^2 \sigma_x^2) + \frac{1}{2} \sum_i \frac{(y_i - m x_i - c)^2}{\sigma_v^2 + \sigma_y^2 + m^2 \sigma_x^2}$$

- with this method Amati et al. (2008, 2009) found an extrinsic scatter $\sigma_{\text{intr}}(\log E_{p,i}) \sim 0.18$ and index and normalization $t \sim 0.5$ and $\sim 100$, respectively
“Standardizing” GRB with $E_{\gamma,i}$-brightness correlations

- 2004: evidence that by substituting $E_{\text{iso}}$ with the collimation corrected energy $E_{\gamma}$ the logarithmic dispersion of the correlation decreases significantly and is low enough to allow its use to standardize GRB (Ghirlanda et al., Dai et al., and many)

\[
\theta = 0.09 \left( \frac{t_{\text{jet},a}}{1 + z} \right)^{3/8} \left( \frac{n_{\gamma}}{E_{\gamma,\text{iso},52}} \right)^{1/8}
\]

\[
E_{\gamma} = (1 - \cos \theta) E_{\gamma,\text{iso}}
\]
the Ep-Eγ correlation is model dependent: slope depends on the assumptions on the circum-burst environment density profile (ISM or wind)

addition of a third observable introduces further uncertainties (difficulties in measuring t_break, chromatic breaks, model assumptions, subjective choice of the energy band in which compute T0.45, inhomogeneity on z of T0.45) and substantially reduces the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)

Nava et al., A&A, 2005: ISM (left) and WIND (right)
- Lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break.
- Challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory modeling of jets?
A tight correlation between $E_{\text{peak}}$, $L_{\text{iso}}$, and time scale $T_{0.45}$ was also claimed, based on still small number of events and proposed for standardizing GRBs (Firmani et al. 2006 and others).
... but Rossi et al. 2008 and Schaefer et al. 2008, based on BeppoSAX and Swift GRBs, showed that the dispersion of the $L_p - E_p - T_{0.45}$ correlation is significantly higher than thought before and that the $E_{p,i} - L_{p,iso} - T_{0.45}$ correlation my be equivalent to the $E_{p,i} - E_{iso}$ correlation.
Ep – “intensity” (or “spectrum-energy”) correlations

- Ep,i – Liso
  - 04
- Ep,i – Eiso
  - “Amati” 02
- Ep,i – Lp,iso
  - “Yonetoku” 04
- Ep,i – E
  - $\gamma$
  - “Ghirlanda” 04
- Ep,i – Eiso-tb
  - “Liang-Zhang” 05
- Ep,i – Lp,iso-T0.45
  - “Firmani” 06

$E_{iso} \leftrightarrow L_{iso}$

$E_{iso} \leftrightarrow L_{p,iso}$

$t_{b, opt} + \text{jet model}$

$t_{b, opt}$

$= T_{0.45}$
Eiso is the GRB brightness indicator with less systematic uncertainties

Lp,iso is affected by the lack of or poor knowledge of spectral shape of the peak emission (the time average spectrum is often used) and by the subjective choice and inhomogeneity in z of the peak time scale

Addition of a third observable introduces further uncertainties (difficulties in measuring t_break, chromatic breaks, model assumptions, subjective choice of the energy band in which compute T_{0.45}, inhomogeneity on z of T_{0.45}) and substantially reduces the number of GRB that can be used (e.g., \#E_{p,i} - E_{\gamma} \sim \frac{1}{4} \#E_{p,i} - E_{iso})

Recent evidences that dispersion of E_{p,i} - L_{p,iso} - T_{0.45} correlation is comparable to that of E_{p,i} - E_{iso} and evidences of outliers / higher dispersion of the E_{p} - E_{\gamma} and E_{p} - E_{iso} - t_{b} correlations

- Ep,i – Liso
  - “Amati” 02
  - Ep,i – Eiso
    - “Ghirlanda” 04
    - Ep,i – Eγ
      - “Liang-Zhang” 05
  - Ep,i – Eiso-tb
    - “Yonetoku” 04
    - Ep,i – Lp,iso
      - “Firmani” 06

- Eiso<->Liso
- Eiso<->Lp,iso
- tb,opt + jet model
- tb,opt
- =
- T0.45
Amati et al. (2008): let’s make a step backward and focus on the Ep,i – Eiso correlation
does the extrinsic scatter of the $E_{p,i}$-$E_{iso}$ correlation vary with the cosmological parameters used to compute $E_{iso}$?

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E N(E) dE \text{ erg}$$

$$D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$

Amati et al. 2008
a fraction of the extrinsic scatter of the $E_{p,i}$-$E_{iso}$ correlation is indeed due to the cosmological parameters used to compute $E_{iso}$

Evidence, independent on SN Ia or other cosmological probes, that, if we are in a flat $\Lambda$CDM universe, $\Omega_m$ is lower than 1

Amati et al. 2008
By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001, D’Agostini 2005)

\[ L(m, c, \sigma_v ; x, y) = \frac{1}{2} \sum_i \log \left( \sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_x^2 \right) + \frac{1}{2} \sum_i \frac{(y_i - m x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_x^2} \]

- \( \Omega_M \) can be constrained to 0.04-0.43 (68%) and 0.02-0.71 (90%) for a flat \( \Lambda \)CDM universe (\( \Omega_M = 1 \) excluded at 99.9% c.l.)

- Significant constraints on both \( \Omega_M \) and \( \Omega_\Lambda \) expected from sample enrichment

Amati et al. 2008
- analysis of the most updated sample of 137 GRBs shows significant improvements w/r to the sample of 70 GRBs of Amati et al. (2008)

- this evidence supports the reliability and perspectives of the use of the $E_{p,i} - E_{iso}$ correlation for the estimate of cosmological parameters

<table>
<thead>
<tr>
<th>$\Omega_m$ (flat universe)</th>
<th>68%</th>
<th>90%</th>
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<tbody>
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<td>70 GRBs (Amati+ 08)</td>
<td>0.04 – 0.43</td>
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<tr>
<td>137 GRBs (Amati+ 12)</td>
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<td>0.03 – 0.54</td>
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![Graphs showing $\Omega_A$ vs. $\Omega_M$ for 70 GRBs and 137 GRBs](image)
**Perspectives**

- Expected significant enlargement of the sample in a few years
  - the simultaneous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample \((z + E_p)\) at a rate of 15-20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters
  - future GRB experiments (e.g., SVOM) and more investigations (physics, methods, calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

Adapted from Amati+ 12 and Ghirlanda+ 2007
Calibrating the Ep,i – Eiso correlation with SN Ia

Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at $z < 1.7$ by using the luminosity distance – redshift relation derived for SN Ia.

The aim is to extend the SN Ia Hubble diagram up to redshift where the luminosity distance is more sensitive to dark energy properties and evolution.

Drawback: with this method GRB are no more an independent cosmological probe.

Kodama et al. 2008

Wang et al. 2012
Investigating correlations involving afterglow properties

(observational gap between “prompt” and “afterglow emission” will be filled by Swift in > 2004)
A correlation between the time, $T_a$, and the luminosity, $L_x$, of the end of the “plateau phase” in GRB X-ray afterglows is being investigated (Dainotti+ 2008, 2010).

A three-parameters correlation between $E_{p,i}$, $E_{iso}$ and $E_{x,iso}$ has been recently reported (Margutti et al. 2012, Bernardini et al. 2012).

If confirmed and refined by further analysis, these correlations may be complementary to the $E_{p,i}$ – intensity correlation for standardizing GRBs.
In the “Swift era”, radio afterglow emission is being detected for about 30% accurately (< a few arcmin) localized GRBs (~93% in X-rays, ~75% in optical/NIR)

Most detections by VLA / EVLA (Frail et al, Chandra et al.); several detections also by WSRT, ATCA, GMRT; a few by VLBA.

The canonical long-duration GRB radio light curve at 8.5 GHz peaks at three to six days in the source rest frame, with a median peak luminosity of $10^{31}$ erg s$^{-1}$ Hz$^{-1}$.

The typical mean fluxes at 8.5 GHz in 5 -10 days from the GRB range from ~100 to ~900 µJy. Peak fluxes may reach 10 mJy.

Chandra & Frail 2012
- **Relevance of radio observations of GRBs**
  - Scintillation: fundamental probe of ultra-relativistic expansion of GRB sources
  - Test of afterglow models unbiased, w/r, e.g., to optical observations (dust extinction, contamination by SN and host galaxy light)

Frail et al. 1997:

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Relevance of radio observations of GRBs

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- Test of afterglow models unbiased, w/r, e.g., to optical observations (dust extinction, contamination by SN and host galaxy light)
- Properties of circum-burst environment
- Late time non relativistic phase expansion (LC and SED): afterglow physics and determination of the blast-wave energy independent of the initial jet collimation
- Statistics of orphan afterglows: inference on maximum jet opening angle

Measure: $F_m, v_m, v_c, v_a, t_{jet}$  ➔  Infer: $E_k, n(r), \varepsilon_e, \varepsilon_B, \theta_{jet}$

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Soderberg et al. 2011
SKA for GRBs

- High sensitivity + high angular resolution + short reaction time + broad band: measurement of GRB source size and expansion velocity through ISM scintillation; accurate location of GRBs in host galaxies; early radio afterglow: physics (reverse shock, transition from optically thick to optically thin synchrotron emission, ...); kinetic energy and jet opening angle from SED fitting; host galaxy radio emission

- High sensitivity: increased number and accuracy of GRBs radio calorimetry; detection of very high z GRBs (up to z 10 ?); study of SFR up to very high z; nearby (z <1 ) low-luminosity GRBs and GRB/SNe;

- Broad FOV: significant number of orphan afterglows -> constraints on distribution of GRB jet opening angles and, hence, of energy budget

Chandra & Frail 2012

Shivers & Berger 2011
SKA for cosmology with GRBs

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- High sensitivity: increased number and accuracy of GRBs radio calorimetry; detection of very high z GRBs (up to z 10 ?); study of SFR up to very high z; nearby (z <1 ) low-luminosity GRBs and GRB/SNe;

- Broad FOV: significant number of orphan afterglows -> **constraints on distribution of GRB jet opening angles and, hence, of energy budget**
Conclusions and perspectives

- Given their huge radiated energies and redshift distribution extending from ~ 0.1 up to > 9, GRBs are potentially a very powerful cosmological probe, complementary to other probes (e.g., SN Ia, clusters, BAO).

- The Ep,i – Eiso correlation is one of the most robust (no firm evidence of significant selection / instrumental effects) and intriguing properties of GRBs and a promising tool for cosmological parameters.

- Analysis in the last years (>2008) provide already evidence, independent on, e.g., SN Ia, that if we live in a flat $\Lambda$CDM universe, $\Omega_m$ is < 1 at >99.9% c.l. ($\chi^2$ minimizes at $\Omega_m \sim 0.25$, consistent with “standard” cosmology).

- The simultaneous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample (z + Ep) at a rate of 15-20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters.

- Future GRB experiments (e.g., SVOM) and more investigations (physics, methods, calibration) will allow to go beyond SN Ia cosm. (e.g., dark energy EOS).

- Radio observations by SKA will give a significant contribution by providing unique clues to the physics, energy budget and beaming angle of GRBs.