Measuring Cosmological Parameters with Gamma-Ray Bursts

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Why looking for more cosmological probes?

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

\[ \Omega = \Omega_m + \Omega_{\text{rel}} + \Omega_\Lambda \]

- Total density parameter
- Mass density including ordinary mass (baryonic mass) plus dark matter.
- Effective mass density of relativistic particles (light plus neutrinos).
- Effective mass density of the dark energy, taking the role described as the cosmological constant.

\[ D_L = (1 + z) c / H_0 \int k^{0.5} \times S \left[ \int k^{0.5} \left[ k(1 + z)^2 + \Omega_M (1 + z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \right] \]
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)
Control of systematics by combination of different probes is fundamental for investigation of DE properties / alternative cosmologies.
The Gamma-Ray Bursts phenomenon

- sudden and unpredictable bursts of hard-X / soft gamma rays with huge flux
- most of the flux detected from 10-20 keV up to 1-2 MeV, with fluences typically of $\sim 10^{-7} - 10^{-4}$ erg/cm$^2$ and bimodal distribution of duration
- measured rate (by an all-sky experiment on a LEO satellite): $\sim 0.8$ / day; estimated true rate $\sim 2$ / day
Early evidences for a cosmological origin of GRBs

- isotropic distribution of GRBs directions
- paucity of weak events with respect to homogeneous distribution in euclidean space
- given the high fluences (up to more than $10^{-4}$ erg/cm² in 20-1000 keV) a cosmological origin would imply huge luminosity
- thus, a “local” origin was not excluded until 1997!
Establishing the cosmological distance scale of GRBs

- **1997**: accurate (a few arcmin) and quick localization of X-ray afterglow -> optical follow-up -> first optical counterparts and host galaxies

- Optical spectroscopy of afterglow and/or host galaxy -> first measurements of GRB redshift
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- redshifts higher than 0.01 and up to > 8
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- fundamental input for origin of long/short
- **redshifts higher than 0.01 and up to > 8:** GRB are cosmological!

- **their isotropic equivalent radiated energy is huge** (up to more than $10^{54}$ erg in a few tens of s)

- **fundamental input for origin of long/short GRB cosmology?**
Are Gamma-Ray Bursts standard candles?

- All GRBs with measured redshift (~320, including a few short GRBs) lie at cosmological distances \((z = 0.033 \text{ – } 9.3)\) (except for the peculiar GRB980425, \(z=0.0085\)).
- Isotropic luminosities and radiated energy are huge, can be detected up to very high \(z\).
- No dust extinction problems; \(z\) distribution much beyond SN Ia but… GRBs are not standard candles (unfortunately).

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Jakobsson et al., 2010

Amati, 2009
jet angles, derived from break time of optical afterglow light curve by assuming standard afterglow model, 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.

$\rightarrow$ more clustered but still not standard (and jet angle estimates very unfirm).

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

\[ E_{\gamma} = (1 - \cos \theta) E_{\gamma, \text{iso}}. \]
The $E_{p,i} – “intensity”$ correlation

- GRB νFν spectra typically show a peak at a characteristic photon energy $E_p$
- measured spectrum + measured redshift $\rightarrow$ intrinsic peak energy and radiated energy

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

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

Amati (2009)
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

162 long GRBs as of June 2013

Swift GRBs
Amati, Frontera & Guidorzi (2009), Amati & Della Valle (2013): the normalization of the correlation varies only marginally using GRBs with known redshift measured by individual instruments with different sensitivities and energy bands.
"Standardizing" GRB with the $E_{p,i}$ - Intensity correlation

\[ E_{p,i} = E_{p,obs} \times (1 + z) \]

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

- not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters

- does the extrinsic scatter and goodness of fit of the $E_{p,i}$-Eiso correlation vary with the cosmological parameters used to compute Eiso?
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 and around 0.3

- strong correlation but significant dispersion of the data around the best-fit power-law; distribution of 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 max likelihood method (D’Agostini 2005) which accounts for sample variance and the uncertainties on both X and Y quantities

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

- with this method Amati et al. (2008, 2009) found an extrinsic scatter $\sigma_{\text{int}}(\log E_{p,i}) \sim 0.2$ and index and normalization $t \sim 0.5$ and $\sim 100$, respectively
By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001)

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

$$\Omega_M$$ could be constrained (Amati+08, 70 GRBs) 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.)

analysis of updated sample of 137 GRBs (Amati+12) 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>best</th>
<th>68%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>70 GRBs (Amati+ 08)</td>
<td>0.27</td>
<td>0.09 – 0.65</td>
<td>0.05 – 0.89</td>
</tr>
<tr>
<td>137 GRBs (Amati+ 12)</td>
<td>0.29</td>
<td>0.12 – 0.54</td>
<td>0.08 – 0.79</td>
</tr>
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</table>
Supernova Cosmology Project

Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)

No Big Bang

Supernovae

GRB

Clusters

CMB

expands forever
recollapses eventually

closed
flat
open

$\Omega_A$

$\Omega_M$
The GRB Hubble diagram extends to much higher $z$ w/r to SNe Ia.

The GRB Hubble diagram is consistent with SNe Ia Hubble diagram at low redshifts: reliability.
All observational cosmology tests agree: ~96% of the Universe is dark.

73% DARK ENERGY

\[ w(z) = w_0 + \frac{w_a z}{1 + z} \]

3% DARK MATTER

3.6% INTERGALACTIC GAS

\[ F(R)R_{\mu\nu}(g) - \frac{1}{2} f(R)g_{\mu\nu} - \nabla_\mu \nabla_\nu F(R) + g_{\mu\nu} \Box F(R) = \kappa^2 T^{(M)}_{\mu\nu} \]
Enlargement of the sample (+ self-calibration)

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

- Future GRB experiments (e.g., SVOM) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy).

<table>
<thead>
<tr>
<th>GRB #</th>
<th>(\Omega_M) (flat)</th>
<th>(w_0) (flat, (\Omega_M=0.3, w_a=0.5))</th>
</tr>
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<tbody>
<tr>
<td>70 (real) GRBs (Amati+ 08)</td>
<td>0.27(^{+0.38}_{-0.18})</td>
<td>(&lt;-0.3) (90%)</td>
</tr>
<tr>
<td>156 (real) GRBs (Amati+ 13)</td>
<td>0.29(^{+0.28}_{-0.15})</td>
<td>(-0.9)(^{+0.4}_{-1.5})</td>
</tr>
<tr>
<td>250 (156 real + 94 simulated) GRBs</td>
<td>0.29(^{+0.16}_{-0.12})</td>
<td>(-0.9)(^{+0.3}_{-1.1})</td>
</tr>
<tr>
<td>500 (156 real + 344 simulated) GRBs</td>
<td>0.29(^{+0.10}_{-0.09})</td>
<td>(-0.9)(^{+0.2}_{-0.8})</td>
</tr>
<tr>
<td>156 (real) GRBs, calibration</td>
<td>0.30(^{+0.06}_{-0.06})</td>
<td>(-1.1)(^{+0.25}_{-0.30})</td>
</tr>
<tr>
<td>250 (156 real + 94 simulated) GRBs, calibration</td>
<td>0.30(^{+0.04}_{-0.05})</td>
<td>(-1.1)(^{+0.20}_{-0.20})</td>
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<tr>
<td>500 (156 real + 344 simulated) GRBs, calibration</td>
<td>0.30(^{+0.03}_{-0.03})</td>
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\[
w(z) = w_0 + \frac{w_a z}{1 + z}
\]
Enlargement of the sample (+ self-calibration + reliable jet angles)

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

- Future GRB experiments (e.g., SVOM) and more investigations (in particular: reliable estimates of jet angles and self-calibration) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g., investigation of dark energy).

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w(z) = w_0 + \frac{w_a z}{1 + z}
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Calibrating the $E_{p,i} - E_{iso}$ 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 $E_{p,i} - E_{iso}$ 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 redshifts at which 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

Amati & Della Valle 13, Amati+ 13
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Kodama et al. 2008

Amati & Della Valle 2013, Amati+ 2013
Conclusions

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

- The $E_p,i$ – intensity correlation is a promising tool for “standardizing” GRBs for measuring cosmological parameters: recent analyses provide already evidence, independent on, e.g., SN Ia, that if we live in a flat $\Lambda$CDM universe, $\Omega_m$ is $\sim 0.3$, consistent with “standard” cosmology.

- Future GRB experiments and investigations will allow to get clues on “dark energy” EOS (cosmological constant vs “quintessence”, etc.) and its evolution, and testing alternative, e.g., $f(R)$, cosmologies.