Measuring Cosmological Parameters with GRBs

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with main contributions by: M. Della Valle, F. Frontera, C. Guidorzi and S. Capozziello

Ioffe Workshop on GRBs and other transient sources: 20 Years of Konus-Wind Experiment

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The accelerating and “dark” Universe

- the standard “hot big-bang” cosmological model as of middle ’90s (general relativity + Hubble law + cosmological principle + dark matter + CMB)

\[ \rho_c(t) = \frac{3H^2(t)}{8\pi G} \]  
Critical density as a function of time. Value below is present value, based on present value of the Hubble parameter \( H \)

\[ \rho_{c,0} = \frac{3H_0^2}{8\pi G} = 9.47 \times 10^{-27} \text{ kg} / \text{m}^3 \]

\( H_0 = 71 \text{ km/s / mpc} \)  
WMAP value for the Hubble parameter.

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

- Total density parameter
  \[ \Omega = \frac{\rho}{\rho_c} \]
  \( \Omega = 1 \) for critical density universe
- Mass density including ordinary mass (baryonic mass) plus dark matter.
- Effective mass density of relativistic particles (light plus neutrinos).
the standard “hot big-bang” cosmological model NOW: inflation + CMB -> ~ flat Universe ($\Omega_{\text{tot}} = 1$), SN Ia (+ clusters, BAO) -> $\Omega_m \sim 0.3$ -> accelerated expansion -> dark energy (cosmological constant, quintessence, ...)

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Omega = \Omega_m + \Omega_{\text{rel}} + \Omega_{\Lambda}$$

- Total density parameter
  $\Omega = \frac{\rho}{\rho_c}$
  $\Omega = 1$ for critical density universe

- 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.

![Diagram of the standard model of cosmology](image)

Dark Matter + Dark Energy affect the expansion of the universe

<table>
<thead>
<tr>
<th>$\Omega_m$</th>
<th>$\Omega_{\Lambda}$</th>
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<tbody>
<tr>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>0.3</td>
<td>0.0</td>
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<tr>
<td>1.0</td>
<td>0.0</td>
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<tr>
<td>5.0</td>
<td>0.0</td>
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Relative size of the universe

Billions of Years
- the Universe expansion is **accelerating**

Universe now expanding ~20% faster than 5 billion years ago

**Models of the Expanding Universe**

- Densely, rapidly decelerating universe
- Sparse, slowly decelerating universe
- Decelerating, then accelerating universe
the Universe is “dark”

All observational cosmology tests agree: ~96% of the Universe is dark

- 73% DARK ENERGY
- 23% DARK MATTER
- 3.6% INTERGALACTIC GAS
- 0.4% STARS, ETC.
A plethora of theoretical answers!
(A tale of unconstrained fantasy)

**DARK MATTER**
- Neutrinos
- WIMPs
- Wimpzillas,
- Axions,
- The “particle forest”.....
- MOND
- MACHOS
- Black Holes
- ......

**DARK ENERGY**
- Cosmological Constant
- Scalar field Quintessence
- Phantom fields
- String-Dilaton scalar field
- Braneworlds
- Unified theories
- ........

![Buridan’s Donkey](image)

Courtesy: Prof. Capozziello (Università Federico II Napoli)
Why looking for more cosmological probes?

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

\[
D_L = (1 + z) c / H_0 \left[ k \right]^{0.5} \times \int S \left[ k \left(1 + z\right)^2 + \Omega_M \left(1 + z'\right)^3 + \Omega_\Lambda \right]^{0.5} \, dz'
\]
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-la and/or bright SNe-Ibc (e.g. HNe)
If the “offset from the truth” is just 0.1 mag....

(slide by M. della Valle)
Why investigating Gamma-Ray Bursts for cosmology?

- All GRBs with measured redshift (~320, including a few short GRBs) lie at cosmological distances \((z = 0.033 - \sim 9.3)\) (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).

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

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

$E_{\gamma} = (1 - \cos \theta) E_{\gamma,\text{iso}}$.
GRB $\nu$F$\nu$ spectra typically show a peak at a characteristic photon energy $E_p$

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

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

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

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

130 long GRBs as of Sept. 2011

BeppoSAX GRBs
Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities.
- 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

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

- 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
Amati, Frontera & Guidorzi (2009): the normalization of the correlation varies only marginally using measures by individual instruments with different sensitivities and energy bands: -> no relevant selection effects
different GRB detectors are characterized by different detection and spectroscopy sensitivity as a function of GRB intensity and spectrum

this may introduce relevant selection effects / biases in the observed $E_{p,i}$ – $E_{iso}$ and other correlations

Adapted from Sakamoto et al. 2011

Band 2008
- Selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, Jakobbson et al. 2010).

- Swift: reduction of selection effects in redshift -> Swift GRBs expected to provide a robust test of the $E_{p,i}$ – $E_{iso}$ correlation.
Fig. 33.— The correlation between $E_{\text{peak}}^{\text{src}}$ and $E_{\text{iso}}$ for the Swift GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E_{\text{peak}}^{\text{src}}$ and $E_{\text{iso}}$ reported by Amati (2006): $E_{\text{peak}}^{\text{src}} = 95 \times (E_{\text{iso}}/10^{52})^{0.49}$.
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.
No evidence of evolution of index and normalization of the correlation with redshift

e.g., Ghirlanda et al. 2008
Correlation of $E_{p,i}$ with other “intensity” indicators

- the correlation holds also when substituting $E_{iso}$ with $L_{iso}$ (e.g., Lamb et al. 2004) or $L_{peak,iso}$ (Yonetoku et al. 2004, Ghirlanda et al., 2005)
- this is expected because $L_{iso}$ and $L_{peak,iso}$ are strongly correlated with $E_{iso}$
- w/r to $E_{iso}$, $L_{p,iso}$ is subject to more uncertainties (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale?)

Nava et al. 2009
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Fig. 3.— The observed correlation between $E_{\gamma, iso}$ and $L_{p,\gamma}$ and for 96 GRBs with known redshift compiled by Yonetoku et al. (2010) The best fit power-law correlation (straight line) has a power-law index 1.13.

imb et al. 2004) or

rves peak at
difficult to
Correlation of \( E_{p,i} \) with other “intensity” indicators

- The correlation holds also when substituting \( E_{iso} \) with \( L_{iso} \) (e.g., Lamb et al. 2004) or \( L_{peak,iso} \) (Yonetoku et al. 2004, Ghirlanda et al., 2005)

- This is expected because \( L_{iso} \) and \( L_{peak,iso} \) are strongly correlated with \( E_{iso} \)

- With respect to \( E_{iso} \), \( L_{p,iso} \) is subject to more uncertainties (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale?)

Nava et al. 2009
the $E_{p,i} - L_{iso}$ and $E_{p,I} - E_{iso}$ correlation holds also within a good fraction of GRBs (Liang et al. 2004, Firmani et al. 2008, Ghirlanda et al. 2009, Li et al. 2012, Frontera et al. 2012, Basak et al. 2013): robust evidence for a physical origin and clues to explanation

Fermi (e.g., Li et al., ApJ, 2012)
the E (Liang et al. 2012 explanation of GRBs)

Implications: emission physics and geometry

- Physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy / Poynting flux dominated fireballs, ...

- E.g., $E_{pk} \propto \Gamma^{-2} t_{\text{var}}^{-1} L^{1/2}$ for synchrotron emission from a power-law distribution of electrons generated in an internal shock (Zhang & Meszaros 2002, Ryde 2005)

- E.g., $E_p \propto R_0^{-1/2} t_j^{-1/4} E_{\text{iso}}^{1/2}$ in scenarios in which for comptonized thermal emission from the photosphere dominates (e.g. Rees & Meszaros 2005, Thomson et al. 2006)
Jet geometry and structure and XRF-GRB unification models (e.g., Lamb et al. 2004)

Viewing angle effects: 
\[ \delta = \left[ \gamma (1 - \beta \cos(\theta v - \Delta \theta)) \right]^{-1}, \]
\[ \Delta E_p \propto \delta, \quad \Delta E_{iso} \propto \delta^{(1+\alpha)} \] (e.g., Yamazaki et al.)

**Uniform/variable jet**

**PL-structured/universal jet**

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Lamb et al. 2005

Yamazaki et al. 2004
Implications: sub-classes of GRBs

Sept. 2012 Ep,i – Eiso plane: 148 long GRBs, 4 XRFs, 13 short GRBs
- Estimates and limits on $E_{p,i}$ and $E_{iso}$ are inconsistent with $E_{p,i}$-$E_{iso}$ correlation holding for long GRBs.
- Low $E_{iso}$ values and high lower limits to $E_{p,i}$ indicate inconsistency also for the other short GRBs.
- Long weak soft emission in some cases, consistent with the $E_{p,i}$ – $E_{iso}$ correlations.

Fig. 1b

GRB0050724
Initial pulse and long tail of GRB 060614 (low-z long GRB without SN) behave in the $E_{p,i} - E_{iso}$ plane like short GRBs.
Initial pulse and long tail of GRB 060614 (low-z long GRB without SN) behave in the $E_{p,i} - E_{iso}$ plane like short GRBs.
**“Standardizing” GRB with the Ep,i - Intensity correlation**

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

\[ D_l = D_l(z, \Omega_M, \Omega_A, \ldots) \]

- 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 Ep,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.

By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001)

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

\[ \Omega_M \] 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>
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<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>
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</table>

![Graphs showing $\Omega_m - \Omega_L$ plots for 70 and 137 GRBs](graph.png)
Perspectives

- present and near future: main contribution expected from joint Fermi + Swift measurements
  - Up to 2009: ~290 Fermi/GBM GRBs, Ep estimates for ~90%, ~35 simultaneously detected by Swift (~13%), 13 with Ep and z estimates (~10% of Swift sample)
  - 2008 pre-Fermi: 61 Swift detections, 5 BAT Ep (8%), 15 BAT + KONUS + SUZAKU Ep estimates (25%), 20 redshift (33%), 11 with Ep and z estimates (~15% of Swift sample)
  - Fermi provides a dramatic increase in Ep estimates (as expected), but a only small fraction of Fermi GRBs is detected / localized by Swift (~15%) -> low number of Fermi GRBs with Ep and z (~5%).
  - Summary: 15-20 GRB/year in the Ep,i – Eiso plane
In the > 2015 time frame a significant step forward expected from SVOM, Lomonosov/UFFO-p, CALET/GBM, LOFT/WFM

- spectral study of prompt emission in 5-5000 keV -> accurate estimates of \( E_p \) and reduction of systematics (through optimal continuum shape determination and measurement of the spectral evolution down to X-rays)

- fast and accurate localization of optical counterpart and prompt dissemination to optical telescopes -> increase in number of \( z \) estimates and reduction of selection effects

- optimized for detection of XRFs, short GRB, sub-energetic GRB, high-\( z \) GRB

- substantial increase of the number of GRB with known \( z \) and \( E_p \) -> test of correlations and calibration for their cosmological use
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 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).

<table>
<thead>
<tr>
<th>GRB #</th>
<th>(\Omega_M) (flat)</th>
</tr>
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</table>
| 70 (real) GRBs (Amati+ 08) | 0.27±0.38
| 156 (real) GRBs (Amati+ 13) | 0.29±0.28
| 250 (156 real + 94 simulated) GRBs | 0.29±0.15
| 500 (156 real + 344 simulated) GRBs | 0.29±0.10
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Adapted from Amati+ 12 and Ghirlanda+ 2007
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.

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

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Drawback: with this method GRB are no more an independent cosmological probe
Other approaches (already partly / to be) investigated

- Cosmographic calibration of the $E_p, i$ – Intensity correlation (e.g., Capozziello et al., Demianski et al.): up to now used to calibrate GRBs against SN Ia, perspectives?

- "Self-calibration" of the correlation with a large enough number of GRBs lying within a narrow ($\Delta z = 0.1-0.2$) range of $z$: promising, requires sample enlargement

- Combining $E_p, i$ – Intensity correlation with other (less tight) GRB correlations (e.g., Schaefer 2007, Mosquera Cuesta et al. 2008, Cardone et al. 2009): more systematics and reduced number of GRBs -> add more noise than information?

- Extending the $E_p$-Intensity correlation by involving other prompt or afterglow properties (e.g., Margutti et al., Tsutsui et al.)

- Investigating other "luminosity" correlations involving prompt and afterglow properties (e.g., $L_x$ – $T_a$ for plateau, Dainotti et al.)
Accounting for collimation

- 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)

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

\[
E_\gamma = (1 - \cos \theta) E_{\gamma,\text{iso}}.
\]
Accounting for collimation: drawbacks

- 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) 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?
Understanding the physical grounds of the correlation

- Ep is a fundamental parameter in GRB prompt emission models

- ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic ($\Gamma > 100$) expansion (fireball or firejet)
- non thermal spectra -> shocks synchrotron emission (SSM)
- fireball internal shocks -> prompt emission
- fireball external shock with ISM -> afterglow emission
e.g., in synchrotron shock models (SSM) it may correspond to a characteristic frequency (possibly $\nu_m$ in fast cooling regime) or to the temperature of the Maxwellian distribution of the emitting electrons.

Galli & Guetta 2007

e.g. in photospheric-dominated emission models it is linked to the temperature of BB photons (direct) or of scattering electrons (Comptonized)

Giannios 2012

• physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy / Poynting flux dominated fireballs, ...

• e.g., \( E_{pk} \propto \gamma^{-2} \tau_{\text{var}}^{-1} L_{1/2} \) for syncrotron emission from a power-law distribution of electrons generated in an internal shock (Zhang & Meszaros 2002, Ryde 2005)

• e.g., \( E_p \propto R_0^{-1/2} t_j^{-1/4} E_{iso}^{1/2} \) in scenarios in which for comptonized thermal emission from the photosphere dominates (e.g. Rees & Meszaros 2005, Thomson et al. 2006)
Conclusions

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

- The \( E_p, i \) – intensity 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 \( \Omega_m \sim 0.3 \), consistent with “standard” cosmology).

- The simulatenous 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 and investigations (physics, collimation, calibration) will allow to go beyond SN Ia (e.g., dark energy EOS).
Stanway et al. 2014
When computing $E_{p,i}$ and $E_{iso}$ based on the fit with Band function (unless CPL significantly better) all *Fermi/GBM* long GRBs with known $z$ are fully consistent with $E_{p,i} - E_{iso}$ correlation as determined with previous / other experiments, both when considering preliminary fits (GCNs) or refined analysis (e.g., Nava et al. 2011).

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Amati 2012

Zhang et al. 2012
Basak et al. 2013: time-resolved $E_{p,i}$ – $E_{iso}$ correlation
Luminosity-Variability correlation (Reichart et al., Guidorzi et al., Rizzuto et al.)

Luminosity-time lag correlation (Norris et al.)
But... is the $E_{p,i}$–intensity correlation real?

- different GRB detectors are characterized by different detection and spectroscopy sensitivity as a function of GRB intensity and spectrum

- this may introduce relevant selection effects / biases in the observed $E_{p,i}$–$E_{iso}$ and other correlations

Adapted from Sakamoto et al. 2011

Band 2008
Selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, Jakobbson et al. 2010).

Swift: reduction of selection effects in redshift -> Swift GRBs expected to provide a robust test of the $E_p,E_{iso}$ correlation.
Swift era: substantial increase of the number of GRBs with known redshift:

- thanks also to combination with other GRB experiments with broad energy band (e.g., Konus/WIND, Fermi/GBM), substantial increase of GRBs in the $E_{p,i} - E_{iso}$ plane

$E_{p,i}$ (keV)

$E_{iso}$ (erg)

Pre-Swift: 37 GRBs
- Selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, Jakobsson et al. 2010).

- Swift: reduction of selection effects in redshift -> Swift GRBs expected to provide a robust test of the $E_{p,i} - E_{iso}$ correlation.
Butler et al. based on analysis of Swift/BAT spectra with a Bayesian method assuming BATSE Ep distribution: 50% of Swift GRB are inconsistent with the pre-Swift Ep,i - Eiso correlation

BUT: comparison of Ep derived by them from BAT spectra using a Bayesian method and those MEASURED by Konus/Wind show that BAT cannot measure Ep > 200 keV (as expected, given its 15-150 keV passband)

MOREOVER: Ep values by Butler et al. NOT confirmed by official analysis by BAT team (Sakamoto et al. 2008) and joint analysis of BAT + KW (Sakamoto et al. 2009) of BAT + Suzaku/WAM (Krimm et al. 2009) spectra.
Ep,i of Swift GRBs measured by Konus-WIND, Suzaku/WAM, Fermi/GBM and BAT (only when Ep inside or close to 15-150 keV and values provided by the Swift/BAT team (GCNs or Sakamoto et al. 2008, 2011): Swift GRBs are consistent with the Ep,i – Eiso correlation

Red points = Swift GRBs

Slope ~ 0.5
σ (logEp,i) ~ 0.2

Gaussian distribution of data scatter
Fig. 33.— The correlation between $E^{\text{src}}_{\text{peak}}$ and $E_{\text{iso}}$ for the Swift GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E^{\text{src}}_{\text{peak}}$ and $E_{\text{iso}}$ reported by Amati (2006): $E^{\text{src}}_{\text{peak}} = 95 \times (E_{\text{iso}}/10^{52})^{0.49}$.

GRB 061021 possible outlier, but Ep based on Konus-WIND analysis of only the first hard pulse - need time-averaged spectral analysis including long soft tail for reliable Ep estimate

No evidence of evolution of index and normalization of the correlation with redshift.
Detection, arcmin localization and **study of GRBs in the GeV energy range** through the **Fermi/LAT instrument**, with dramatic improvement w/r CGRO/EGRET.

Detection, rough localization (a few degrees) and **accurate determination** of the shape of the spectral continuum of the prompt emission of GRBs from 8 keV up to 30 MeV through the Fermi/GBM instrument.

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**Large Area Telescope (LAT)**
- Pair conversion telescope.
- Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV.

**Gamma-ray Burst Monitor (GBM)**
- 12 NaI detectors, 2 BGO detectors.
- Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.

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"Typical" Prompt GRB Spectrum

- $E^2 N_E$ (erg cm$^{-2}$ s$^{-1}$)

- Photon Energy (MeV)

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February 02, 2009
L. Baldini
Rencontres de Moriond, 2009
Gruber et al. (2011, official Fermi team): all Fermi/GBM long GRBs with known $z$ are consistent with $E_{p,i} - E_{\text{iso}}$ correlation, short GRBs are not.

Slight overestimate of normalization and dispersion possibly due to the use, for some GRBs, of the CPL model instead of the Band model ($\rightarrow$ overestimate of $E_p$, underestimate of $E_{\text{iso}}$).
When computing $E_{p,i}$ and $E_{iso}$ based on the fit with Band function (unless CPL significantly better) all Fermi/GBM long GRBs with known $z$ are fully consistent with $E_{p,i} - E_{iso}$ correlation as determined with previous / other experiments, both when considering preliminary fits (GCNs) or refined analysis (e.g., Nava et al. 2011).
Amati, Frontera & Guidorzi (2009): the normalization of the correlation varies only marginally using GRBs with known redshift measured by individual instruments with different sensitivities and energy bands.
the $E_{p,i}$–$L_{iso}$ correlation holds also within a good fraction of GRBs (Liang et al., 2004, Firmani et al., 2008, Ghirlanda et al., 2009, Li et al., 2012, Frontera et al., 2012): robust evidence for a physical origin and clues to explanation.


Fermi (e.g., Li et al., ApJ, 2012)
Basak et al. 2013: time-resolved $E_{\text{p, i}}$ – $E_{\text{i, iso}}$ correlation
GRBs WITHOUT measured redshift

- claims that a high fraction of BATSE events (without z) are inconsistent with the correlation (e.g. Nakar & Piran 2005, Band & Preece 2005, Kaneko et al. 2006, Goldstein et al. 2010)

- but... is it plausible that we are measuring the redshift only for the very small fraction (10-15%) of GRBs that follow the Ep,i – Eiso correlation? This would imply unreliably huge selection effects in the sample of GRBs with known redshift

- in addition: Ghirlanda et al. (2005), Bosnjak et al. (2005), Nava et al. (2008), Ghirlanda et al. (2009) showed that most BATSE GRBs with unknown redshift are potentially consistent with the correlation

- moreover: the existence of an Ep,i – Eiso correlation was supposed by Lloyd, Petrosian & Mallozzi in 2001 based on BATSE data
using GRBs with unknown redshift -> convert the $E_{p,i}$ – $E_{iso}$ correlation into an $E_{p,obs}$ – Fluence correlation

Intrinsic (cosm. Rest-frame) plane

Observer’s plane

GRBs WITH redshift (130)

GRBs WITHOUT redshift (thousands)
method: unknown redshift -> convert the Ep,i – Eiso correlation into an Ep,obs – Fluence correlation

\[ E_{\text{peak}}^{\text{obs}}(1+z) = k \left( \frac{4\pi d_L^2 F}{1+z} \right)^a \rightarrow E_{\text{peak}}^{\text{obs}} = kF^a f(z); \quad f(z) = \frac{(4\pi d_L^2)^a}{(1+z)^{1+a}} \]

the fit of the updated Ep,i – Eiso GRB sample with the maximum likelihood method accounting for extrinsic variance provides \(a=0.53, k=102, \sigma = 0.19\)

for these values \(f(z)\) maximizes for \(z\) between 3 and 5
Amati, Dichiara et al. (2013, in prep.): consider fluences and spectra from the Goldstein et al. (2010) BATSE complete spectral catalog (on line data)

considered long (777) and short (89) GRBs with fit with the Band-law and uncertainties on Ep and fluence < 40%

- most long GRBs are potentially consistent with the $E_{p,i} - E_{iso}$ correlation, most short GRBs are not

![Graph showing $E_{p,i}$ vs. Energy Fluence for long and short GRBs.](image)
ALL long GRBs with 20% uncertainty on Ep and fluence (525) are potentially consistent with the correlation.
measure only the harder portion of the event: overestimate of $E_p$ and underestimate of the fluence
Amati, Dichiara et al. (2011, in prep.): MC simulations assuming the existence and the measured parameters of the $E_{p,i} - E_{iso}$ correlation and accounting for the observed distributions ($E_{iso}$, $z$, $E_{iso}$ vs. $z$) and BATSE instrumental sensitivity as a function of $E_p$ (Band 2003-2009).

When accounting for spectral evolution, i.e. $E_p = f(\text{Flux})$, the small fraction of “outliers” in the $E_{p,\text{obs}} - \text{Fluence}$ plane is reproduced.
Liang et al. 2004: evidence for an $E_p$ – Flux correlation within most BATSE GRBs and, based on pseudo-redshifts, possible existence of a univoque $E_{p,i}(t)$ – $L_{iso}(t)$ correlation.
The $E_{\text{p,i}} - L_{\text{iso}}$ correlation holds also within a good fraction of GRBs (Liang et al. 2004, Firmani et al. 2008, Ghirlanda et al. 2010, Li et al. 2012, Frontera et al. in press): cannot be explained by selection effects -> robust evidence for a physical origin of $E_{\text{p,i}}$ – Intensity correlations and clues to physical explanation.

GRB980425 not only prototype event of GRB/SN connection but closest GRB \((z = 0.0085)\) and sub-energetic event \((E_{\text{iso}} \sim 10^{48} \text{ erg}, E_{\text{k,aft}} \sim 10^{50} \text{ erg})\)

GRB031203: the most similar case to GRB980425/SN1998bw: very close \((z = 0.105)\), SN2003lw, sub-energetic
the most common explanations for the (apparent?) sub-energetic nature of GRB980425 and GRB031203 and their violation of the $E_{\text{p,i}}$ – $E_{\text{iso}}$ correlation assume that they are NORMAL events seen very off-axis (e.g. Yamazaki et al. 2003, Ramirez-Ruiz et al. 2005)

$$\delta = \left[ \gamma (1 - \beta \cos (\theta v - \Delta \theta)) \right]^{-1}, \Delta E_{\text{p}} \propto \delta, \Delta E_{\text{iso}} \propto \delta^{(1+\alpha)}$$

$$\alpha = 1 \div 2.3 \rightarrow \Delta E_{\text{iso}} \propto \delta^{(2 \div 3.3)}$$

GRB 060218, a very close (z = 0.033, second only to GRB980425), with a prominent association with SN2006aj, and very low Eiso (6 x 10^{49} erg) and Ek,aft - > very similar to GRB980425 and GRB031203

but, contrary to GRB980425 and (possibly) GRB031203, GRB060218 is consistent with the Ep,i-Eiso correlation -> evidence that it is a truly sub-energetic GRB -> likely existence of a population of under-luminous GRB detectable in the local universe

also XRF 020903 is very weak and soft (sub-energetic GRB prompt emission) and is consistent with the Ep-Eiso correlation

Amati et al., 2007
GRB060218 was a very long event (~3000 s) and without XRT measurement (0.3-10 keV) $E_{p,i}$ would have been over-estimated and found to be inconsistent with the $E_{p,i}$-$E_{iso}$ correlation.

Ghisellini et al. (2006) found that a spectral evolution model based on GRB060218 can be applied to GRB980425 and GRB031203, showing that these two events may be also consistent with the $E_{p,i}$-$E_{iso}$ correlation.

Sub-energetic GRB consistent with the correlation; apparent outliers(s) GRB 980425 (GRB 031203) could be due to viewing angle or instrumental effect.
Nava et al. 2012: $E_{p,i} - E_{i,iso}$ and $E_{p} - L_{p,iso}$ correlations confirmed by the analysis of the complete sample by Salvaterra et al. 2011 - further evidence of low impact of selection effects in redshift.

GRB 061021 possible outlier, but $E_p$ based on Konus-WIND analysis of only the first hard pulse - need time-averaged spectral analysis including long soft tail for reliable $E_p$ estimate.