Cosmologia con i GRB ?

Lorenzo Amati

(INAF – IASF Bologna)

SAIt - Società Astronomica Italiana - INAF - Istituto Nazionale di Astrofisica

LVIII Congresso SAIt - MILANO - 13-16 maggio 2014 - Palazzo Cusani via Brera 15

"Strutture cosmiche: dal Sistema Solare ai confini dell'Universo"

Measuring Cosmological Parameters with Gamma-Ray Bursts

Lorenzo Amati

(INAF – IASF Bologna)

SAIt - Società Astronomica Italiana - INAF - Istituto Nazionale di Astrofisica

LVIII Congresso SAIt - MILANO - 13-16 maggio 2014 - Palazzo Cusani via Brera 15

"Strutture cosmiche: dal Sistema Solare ai confini dell'Universo"

Why looking for more cosmological probes ?

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

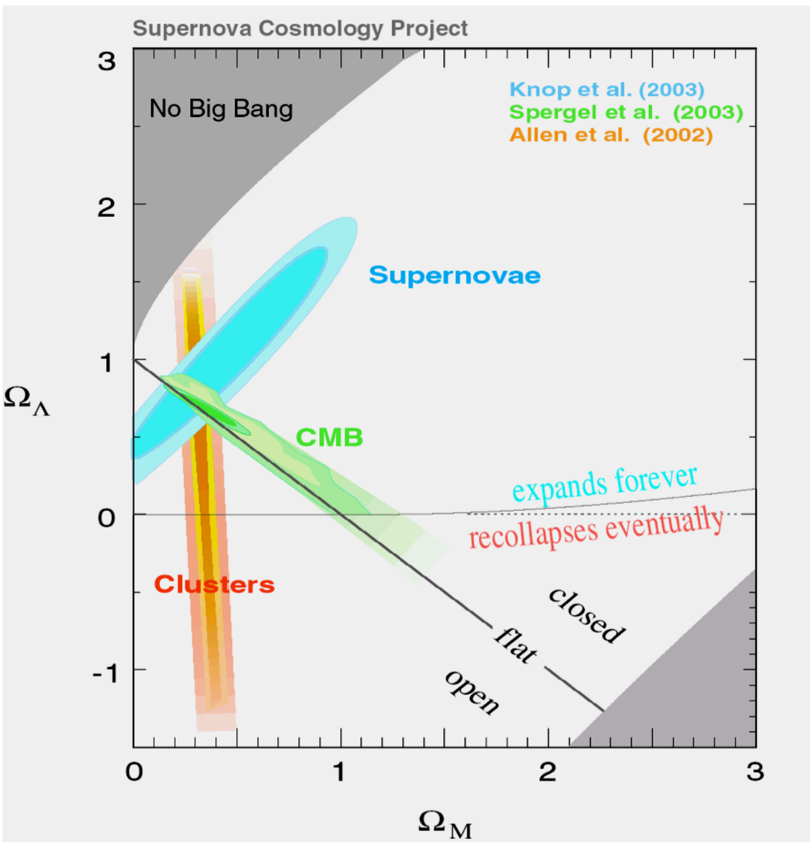
$$\Omega = \Omega_m + \Omega_{rel} + \Omega_\Lambda$$

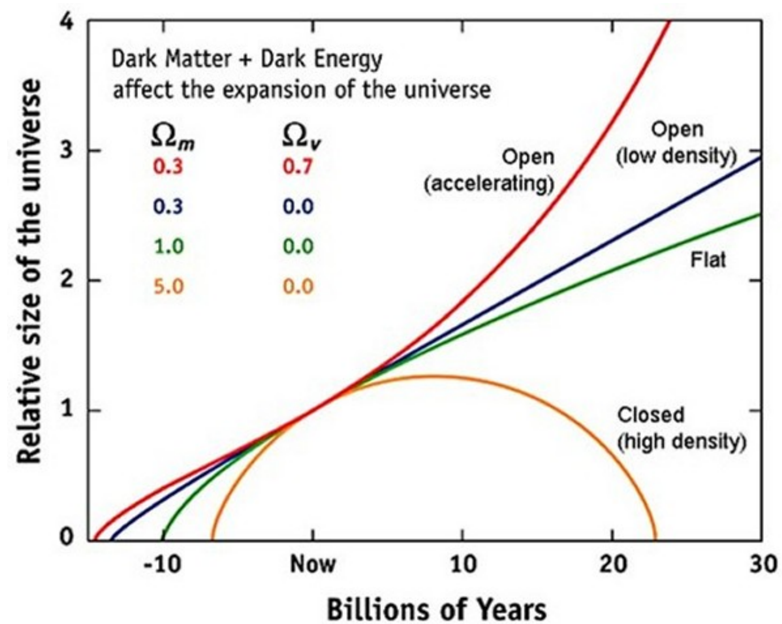
Total density parameter $\Omega = \frac{\rho}{\rho_c}$; $\Omega = 1$ for critical density universe

Ω_m: Mass density including ordinary mass (baryonic mass) plus dark matter.

Ω_{rel}: Effective mass density of relativistic particles (light plus neutrinos).

Ω_Λ: Effective mass density of the dark energy, taking the role described as the cosmological constant.





$$D_L = (1+z)c \div H_o \,|k|^{0.5} \times S\left\{ |k|^{0.5} \int_0^z \left[k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \right\}$$

❑ **Each cosmological probe is characterized by possible systematics**

❑ **e.g SN Ia:**

➢ different explosion mechanism and progenitor systems ? May depend on z ?

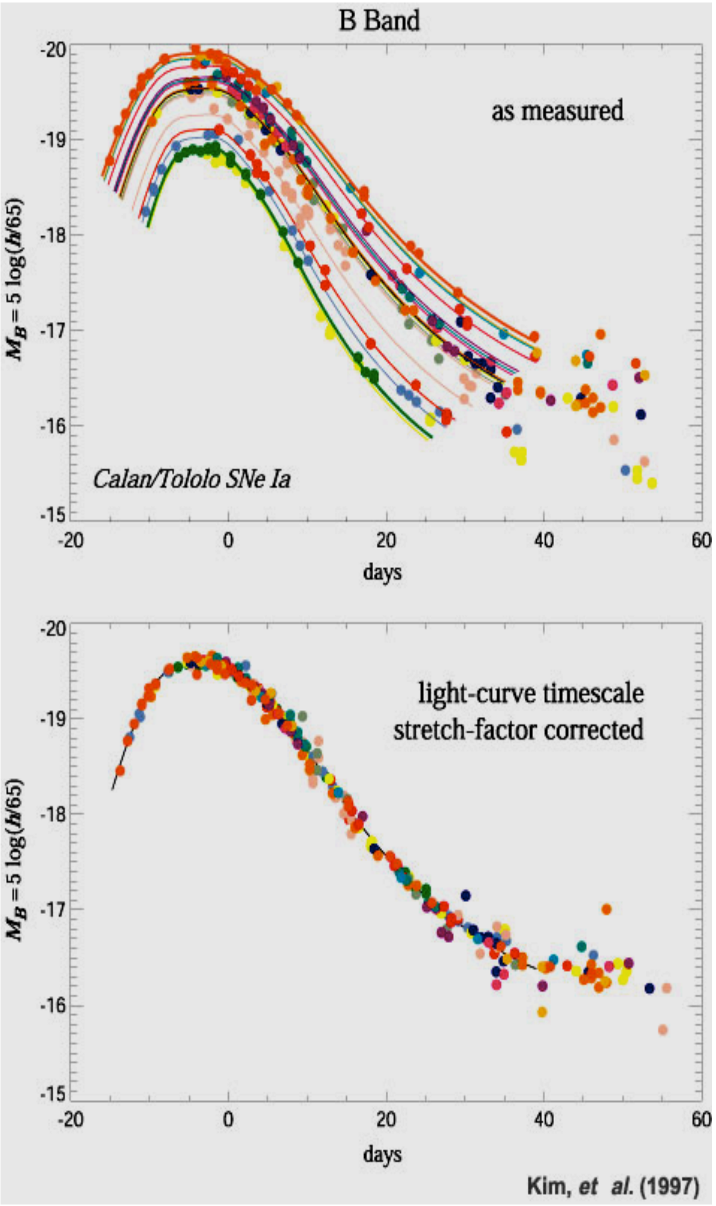
➢ light curve shape correction for the luminosity normalisation may depend on z

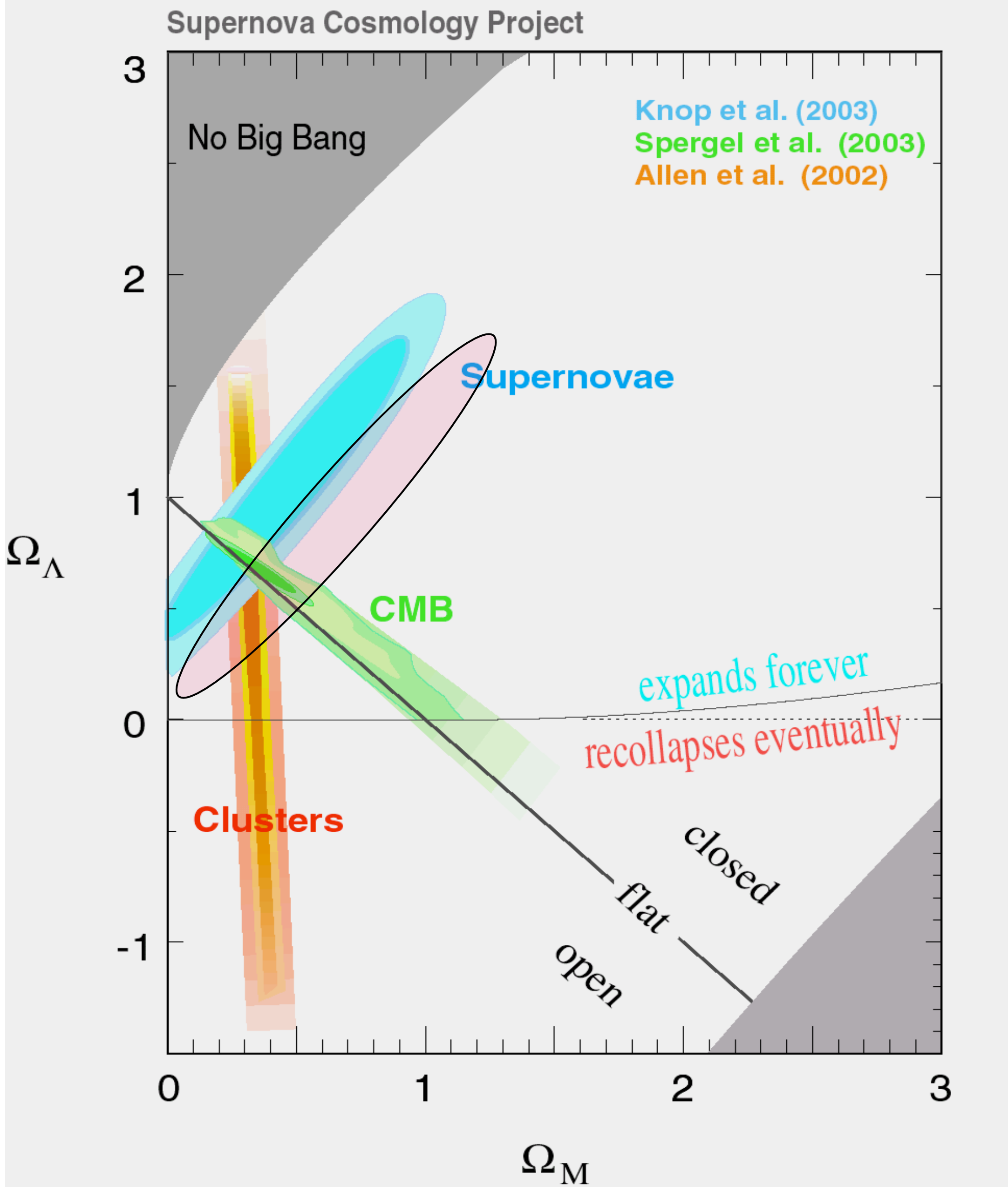
➢ signatures of evolution in the colours

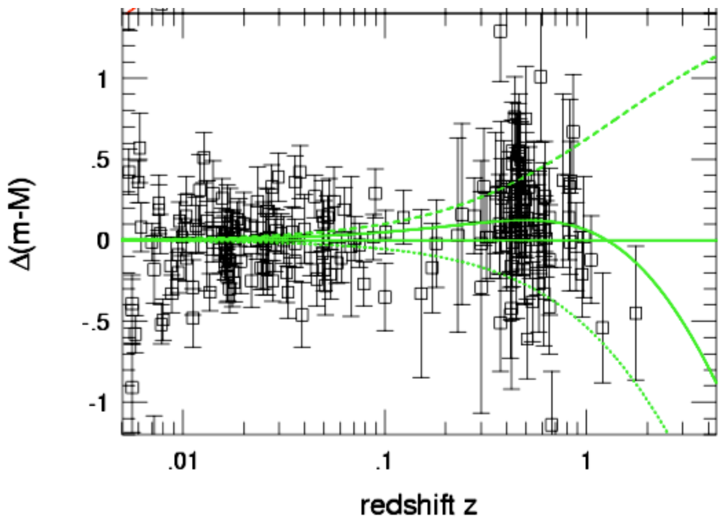
➢ correction for dust extinction

➢ anomalous luminosity-color relation

➢ contaminations of the Hubble Diagram by no-standard SNe-Ia and/or bright SNe-Ibc (e.g. HNe)





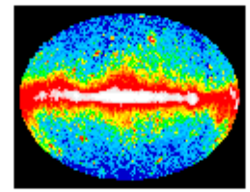


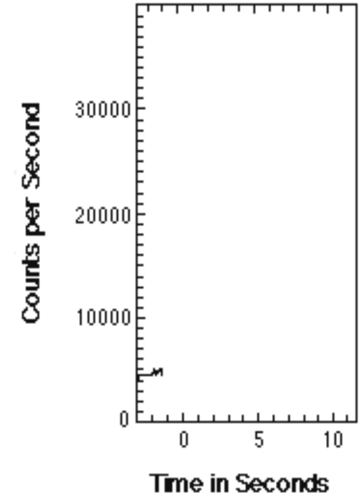
If the "offset from the truth" is just 0.1 mag….

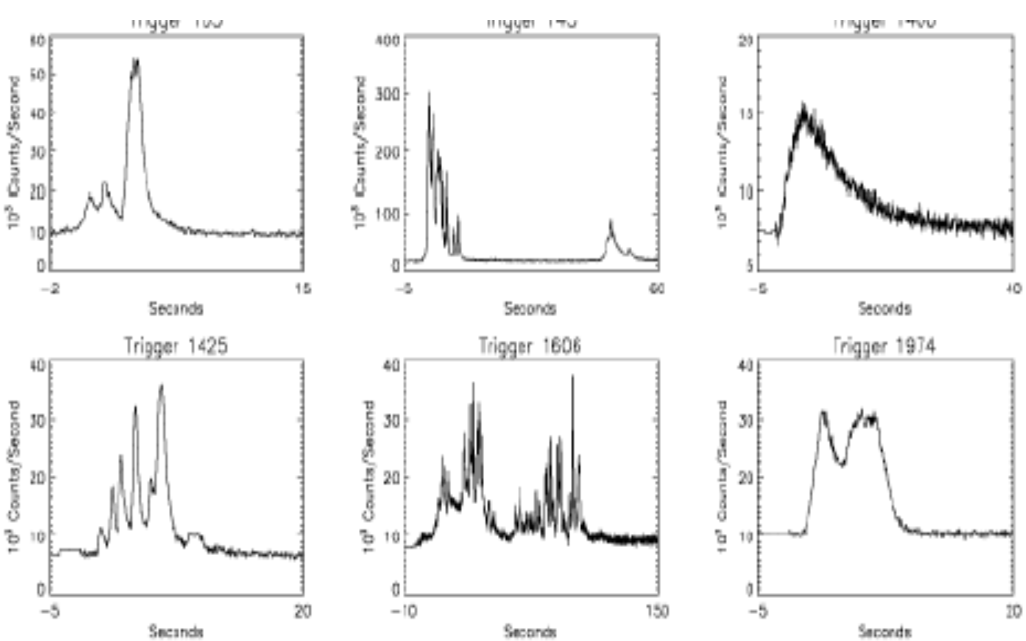
(slide by M. della Valle)

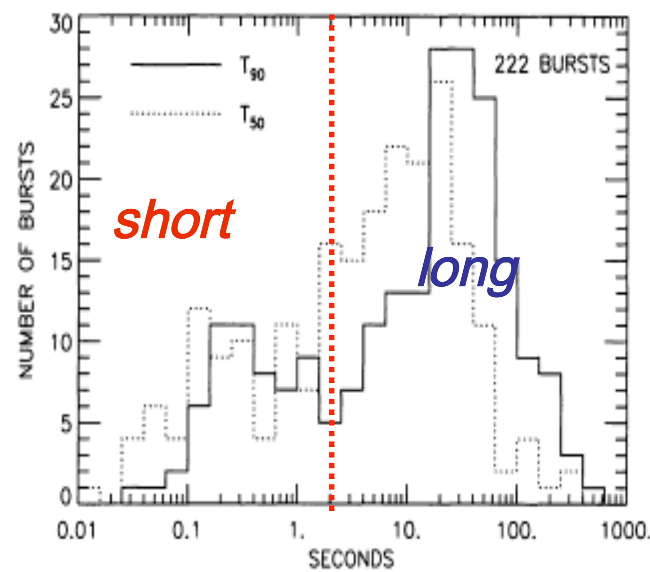
The Gamma-Ray Burst phenomenon

- ❑ 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 ~10^{-7} – 10^{-4} erg/cm^2 and bimodal distribution of duration
- ❑ measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day



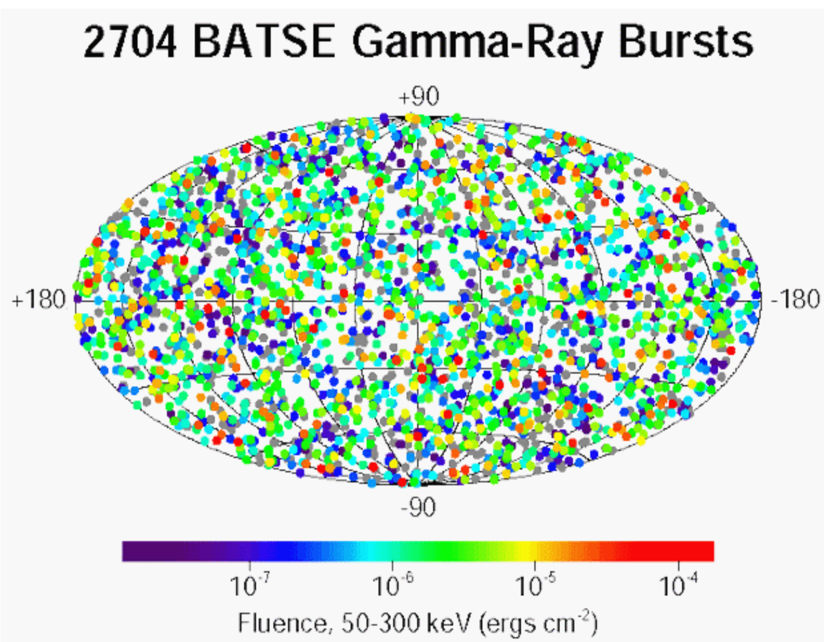


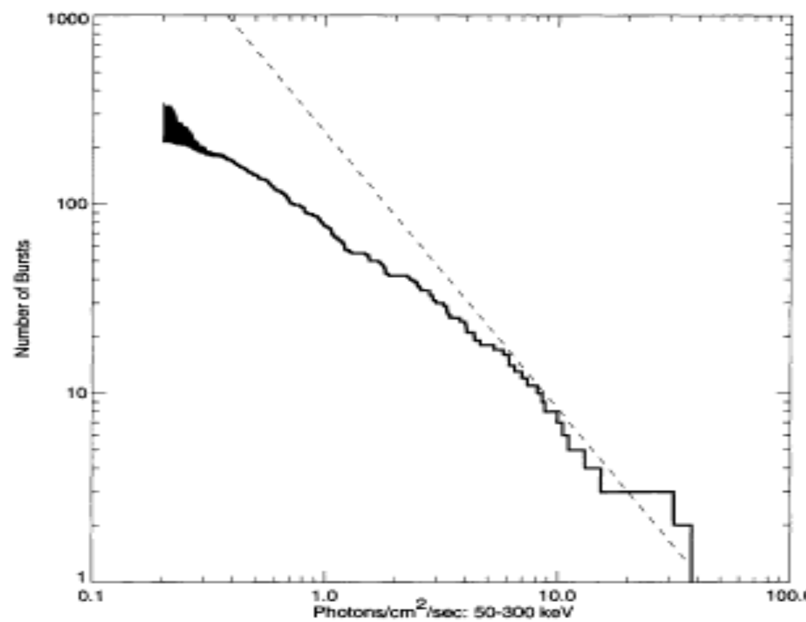




Early evidences for a cosmological origin of GRBs

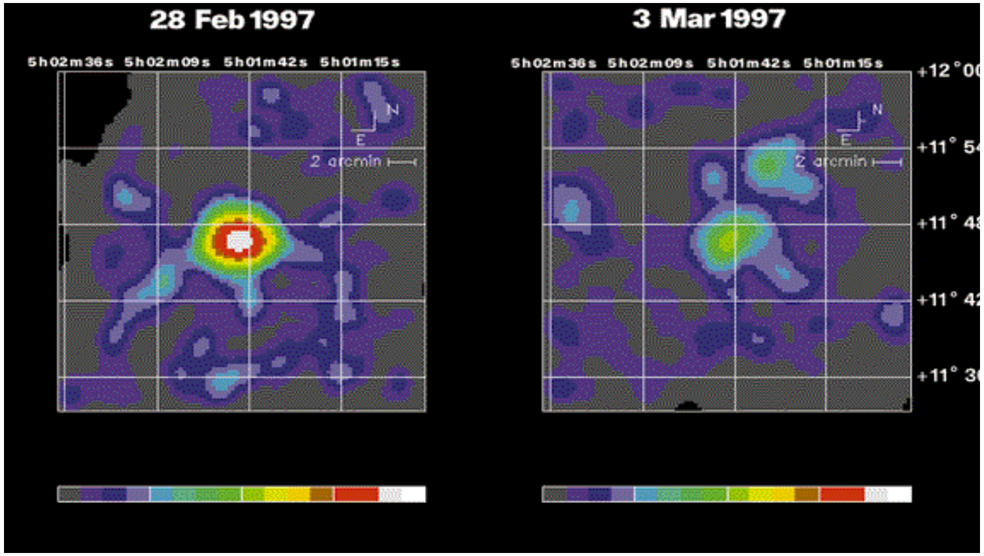
- isotropic distribution of GRBs directions
- paucity of weak events with respect to homogeneous distribution in euclidean space
- **given the high fluences (up to more than 10^{-4} erg/cm2 in 20-1000 keV) a cosmological origin would imply huge luminosity**
- thus, a "local" origin was not excluded until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

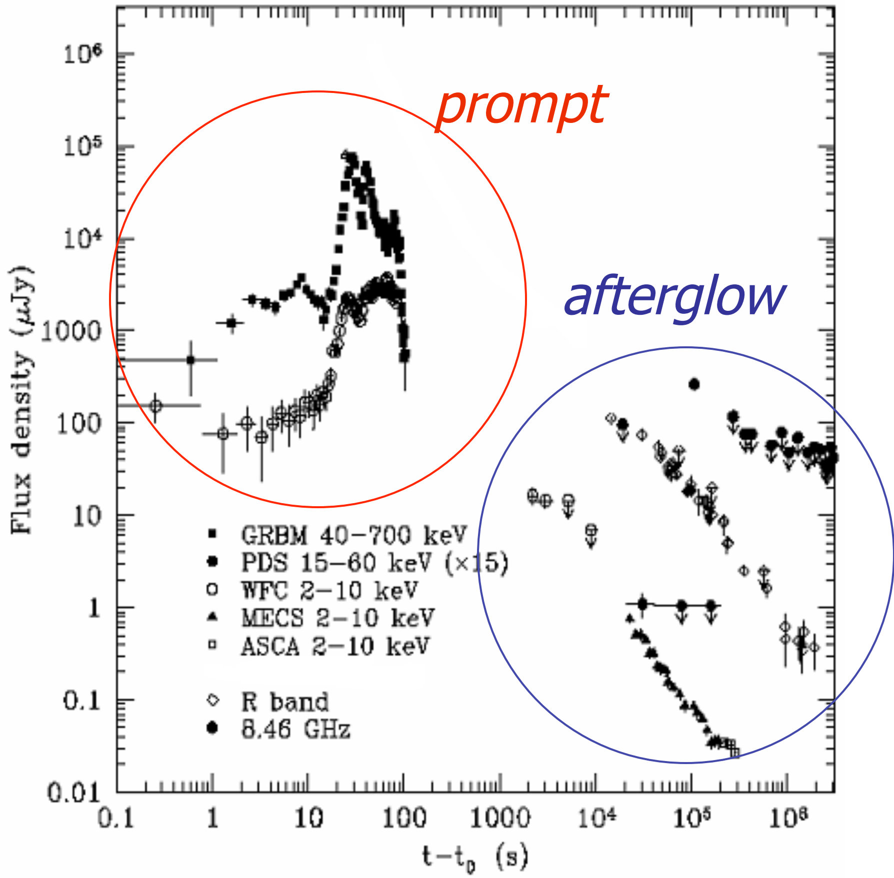




Establishing the GRBs cosmological distance scale

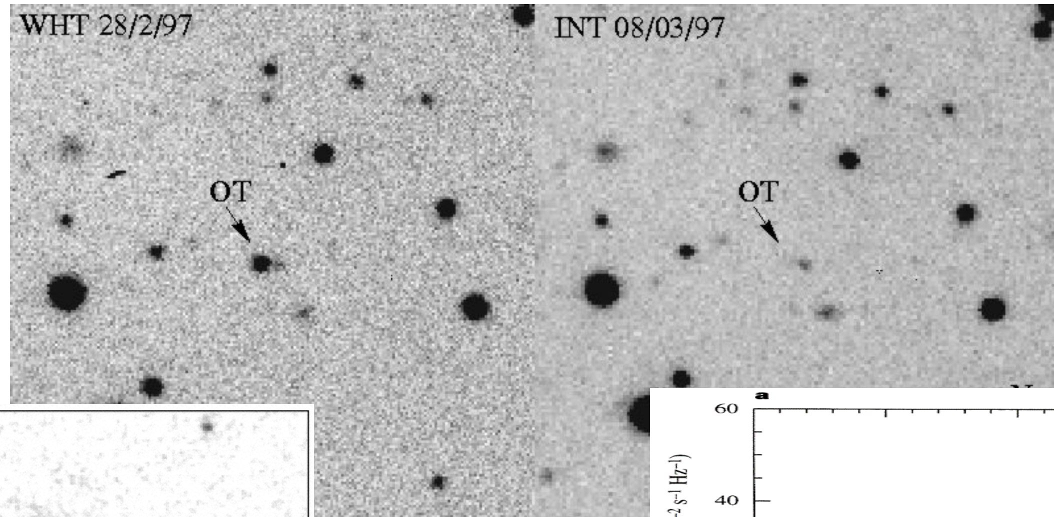
❑ in 1997 discovery of afterglow emission and first systematic arcmin location by BeppoSAX

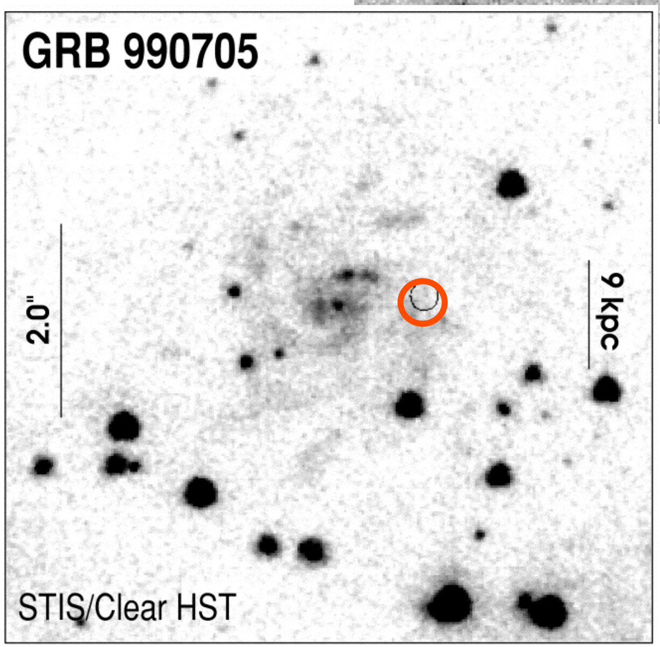


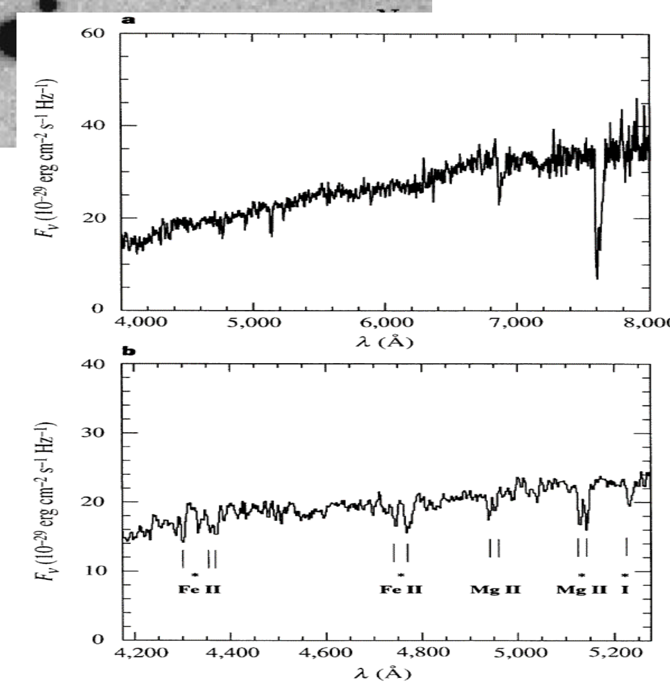


- ❑ **1997:** accurate (a few arcmin) and quick localization of X-ray afterglow -> optical follow-up -> first optical counterparts and host galaxies

- ❑ optical spectroscopy of afterglow and/or host galaxy –> **first measurements of GRB redshift**



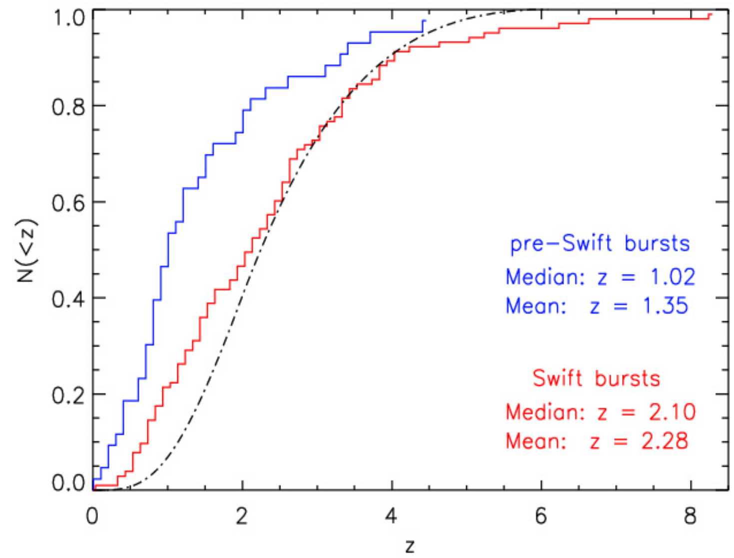




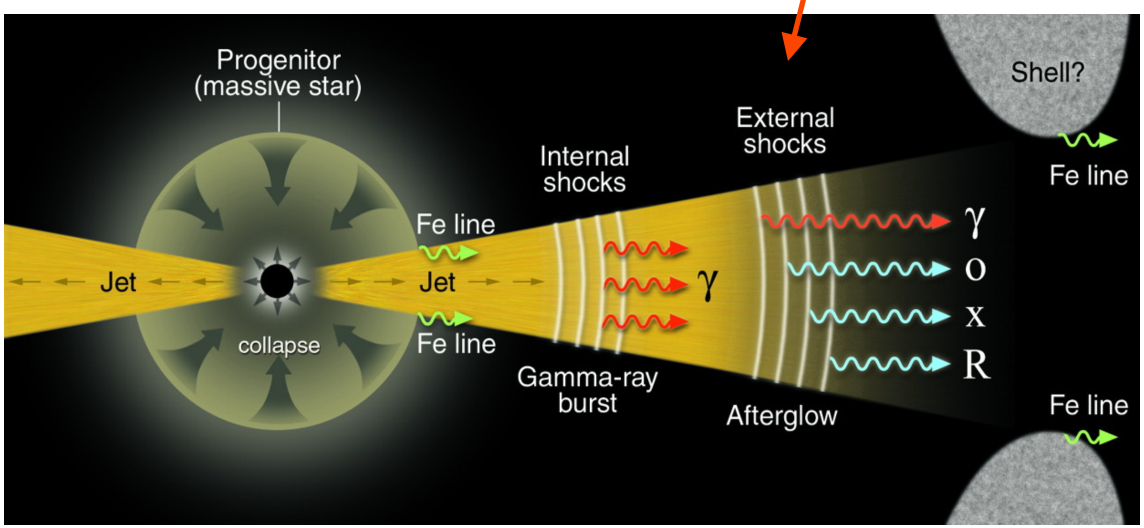
- redshifts higher than 0.01 and up to > 8: GRB are cosmological !

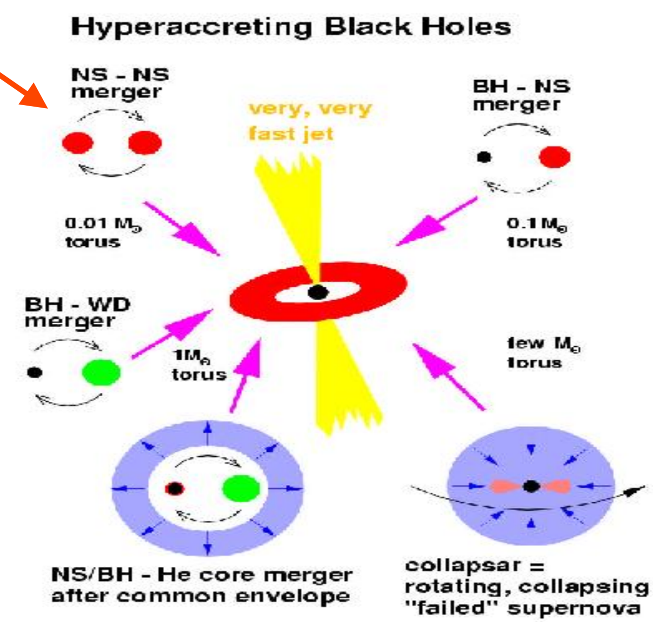
- their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s !)

- fundamental input for origin of long / short



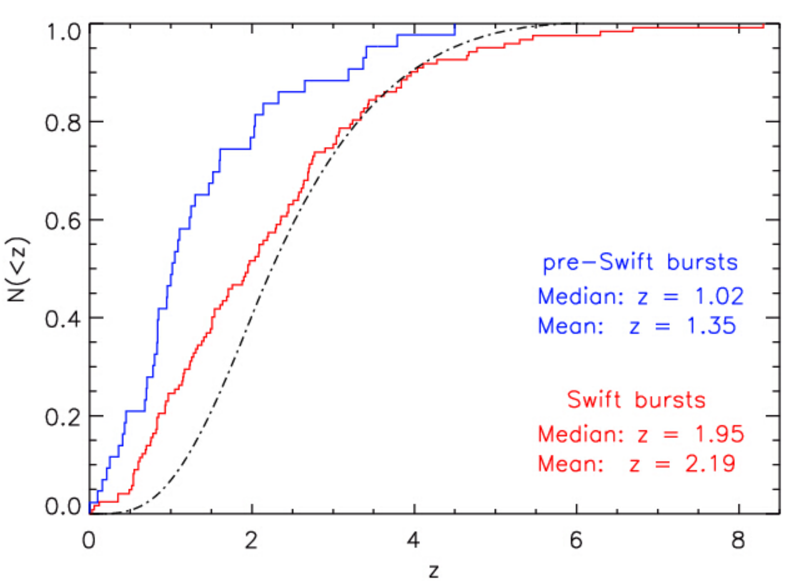
GRB COSMOLOGY ?



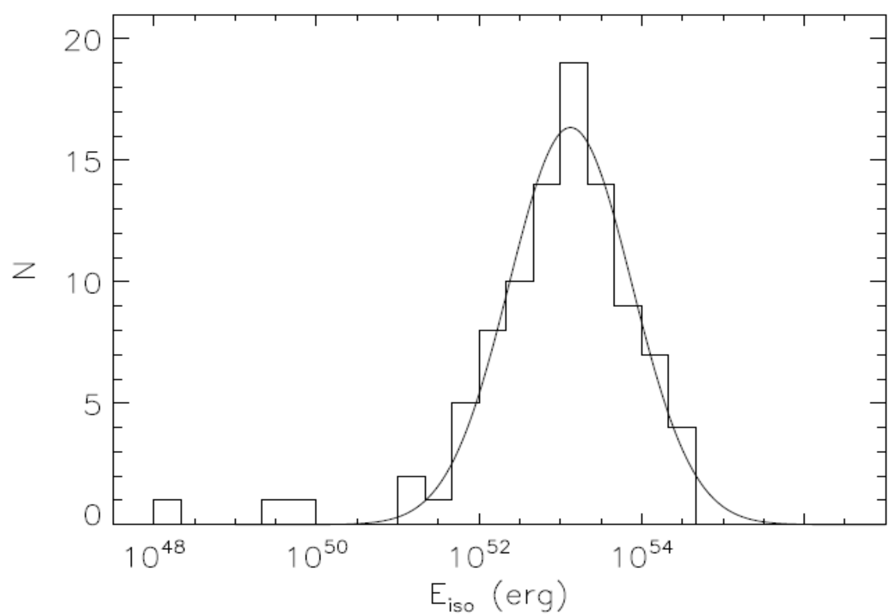


Why investigating Gamma-Ray Bursts for cosmology ?

- all GRBs with measured redshift (~320, including a few short GRBs) lie at cosmological distances **(z = 0.033 – ~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)**



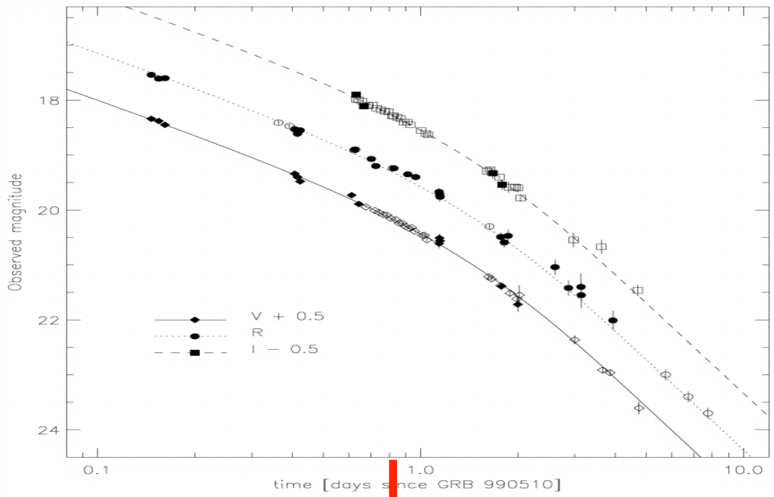
Jakobsson et al., 2010



Amati, 2009

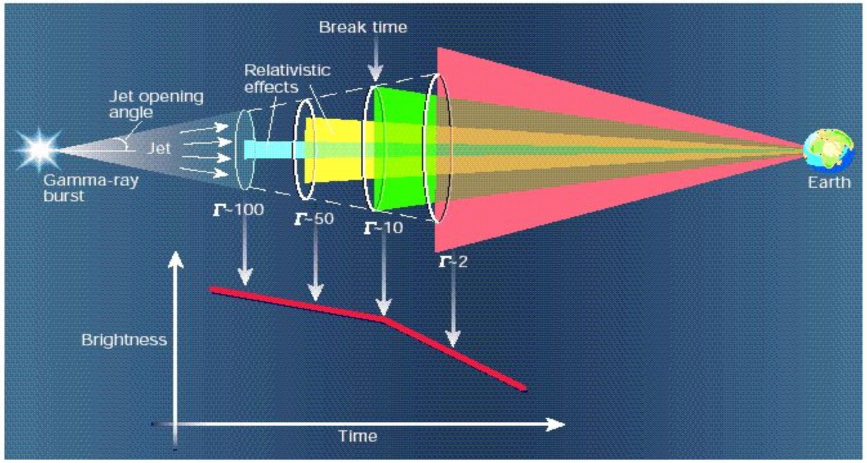
- jet angles, derived from break time of optical afterglow light curve by assuming standard afterglow model, are of the order of few degrees
- the collimation-corrected radiated energy spans the range ~5x10[49] – 5x10[52] erg

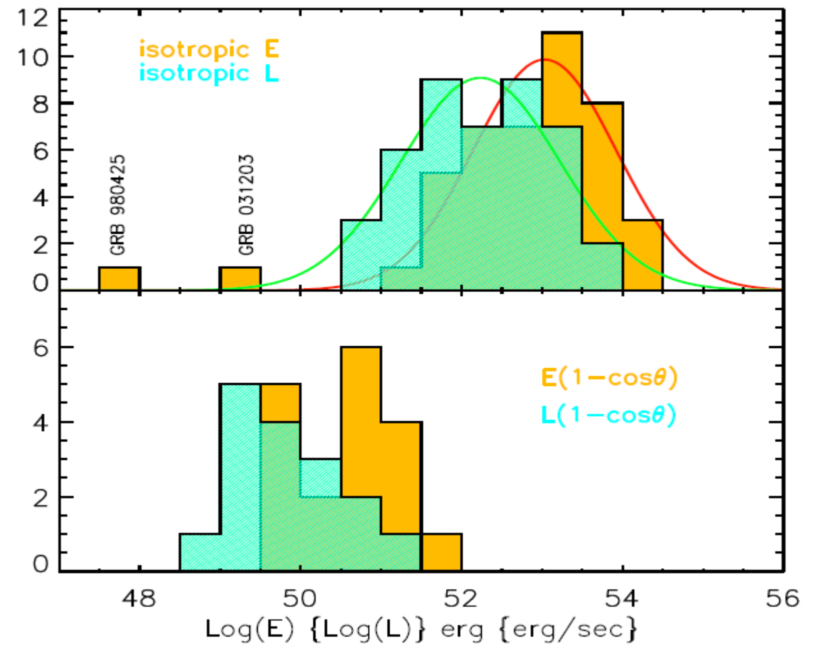
-> more clustered but still not standard



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

$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$



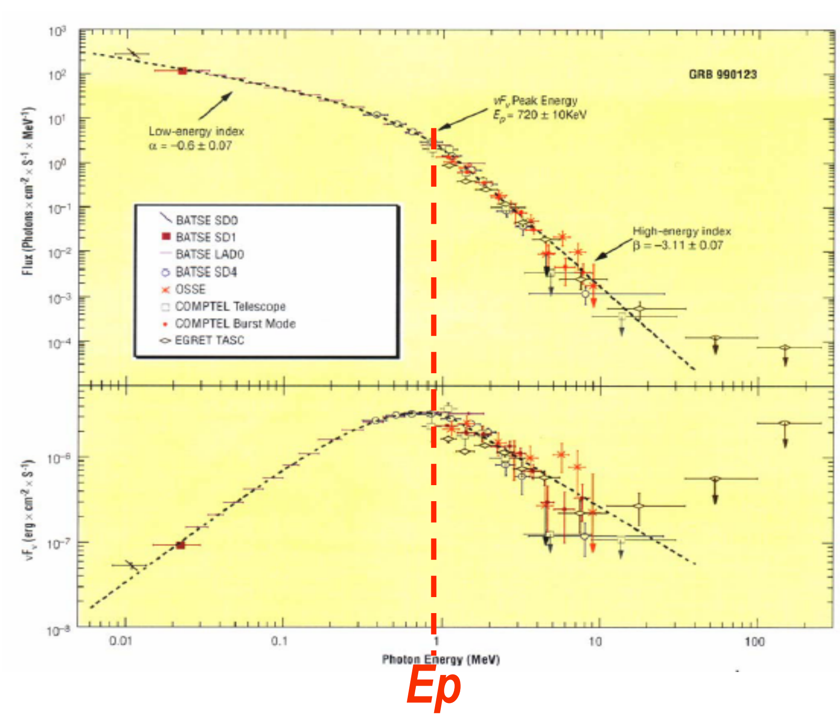


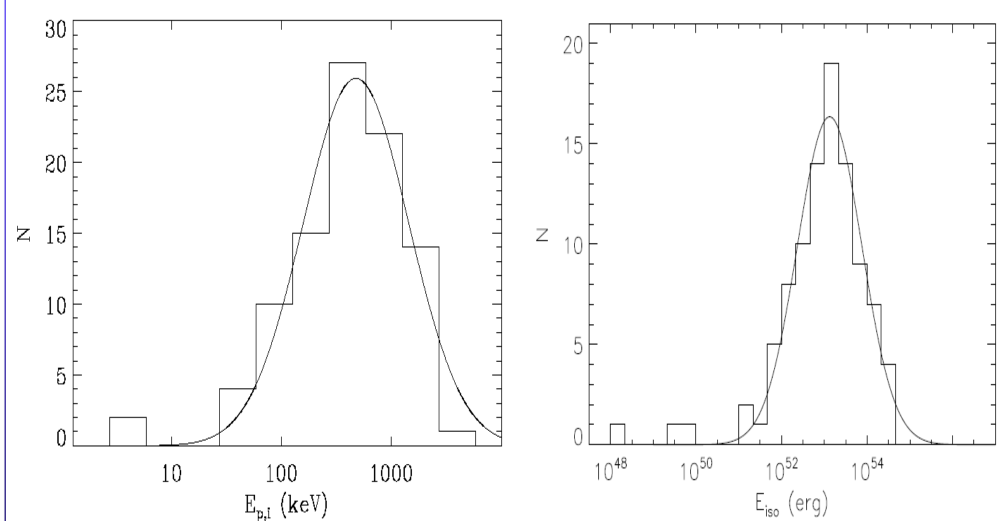
The Ep,i – "intensity" correlation

- GRB νFν spectra typically show a peak at a characteristic photon energy E_p
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

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

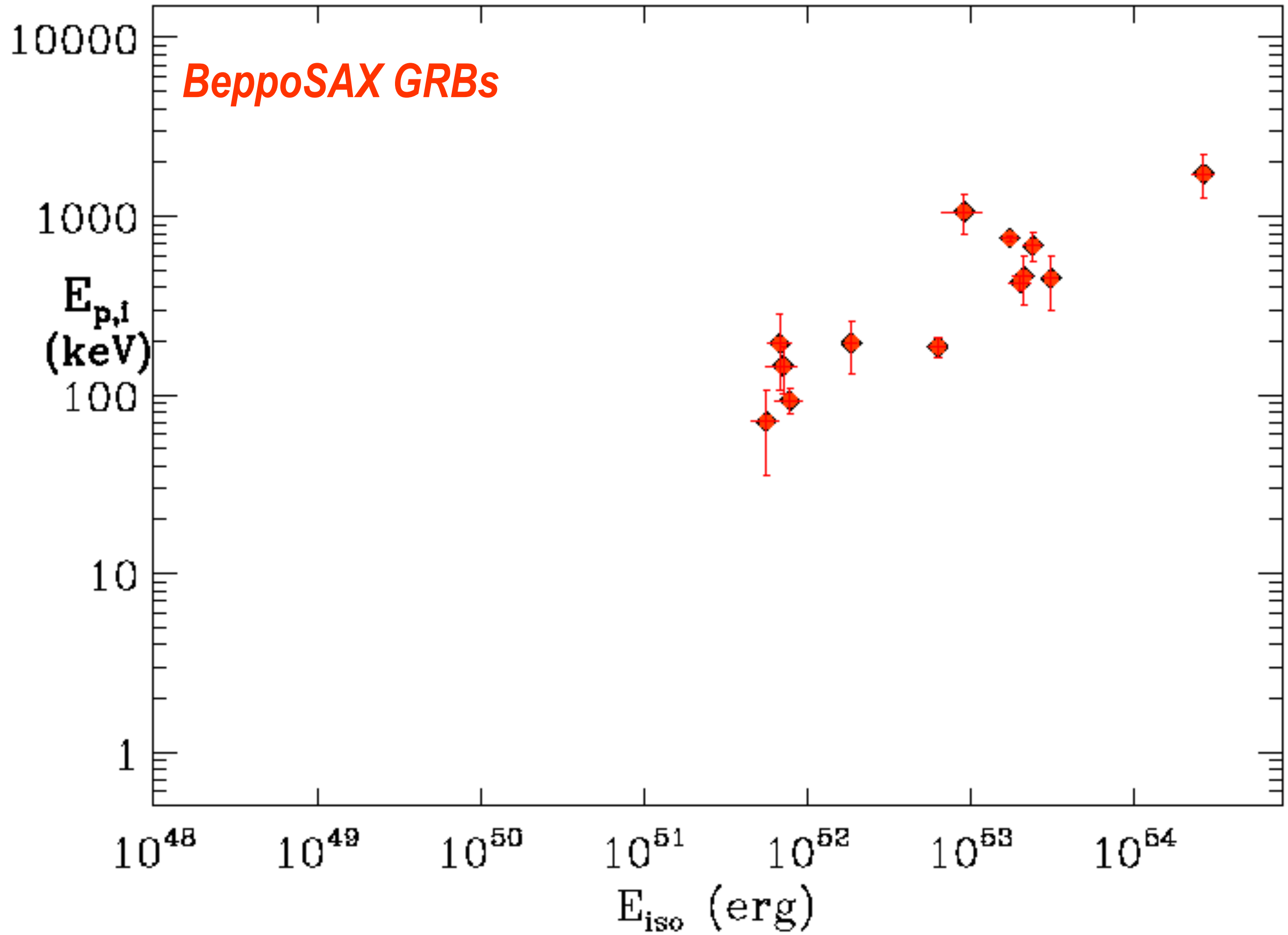
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$





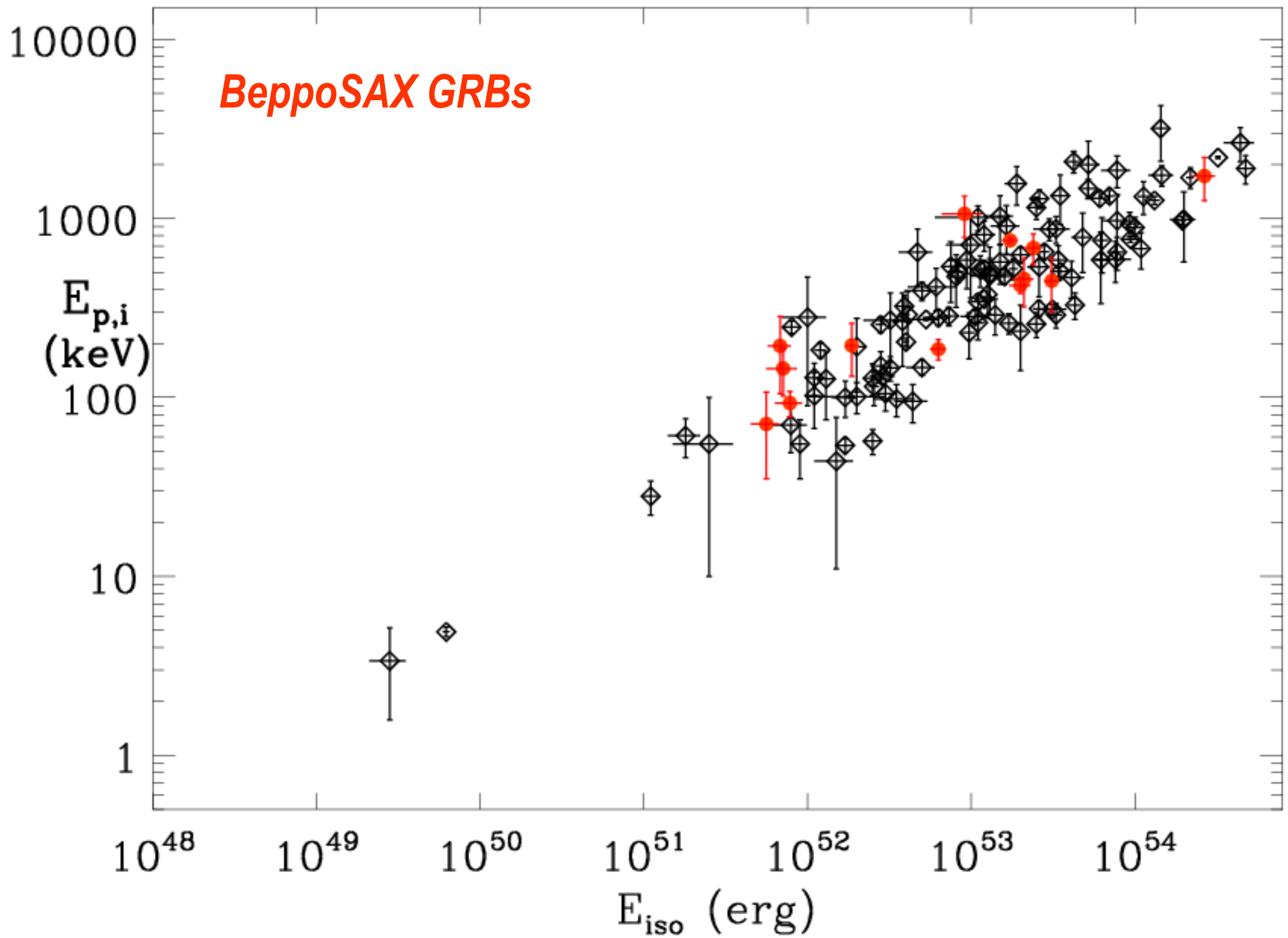
Amati (2009)

➢ Amati et al. (A&A 2002): significant correlation between Ep,i and Eiso found based on a small sample of BeppoSAX GRBs with known redshift



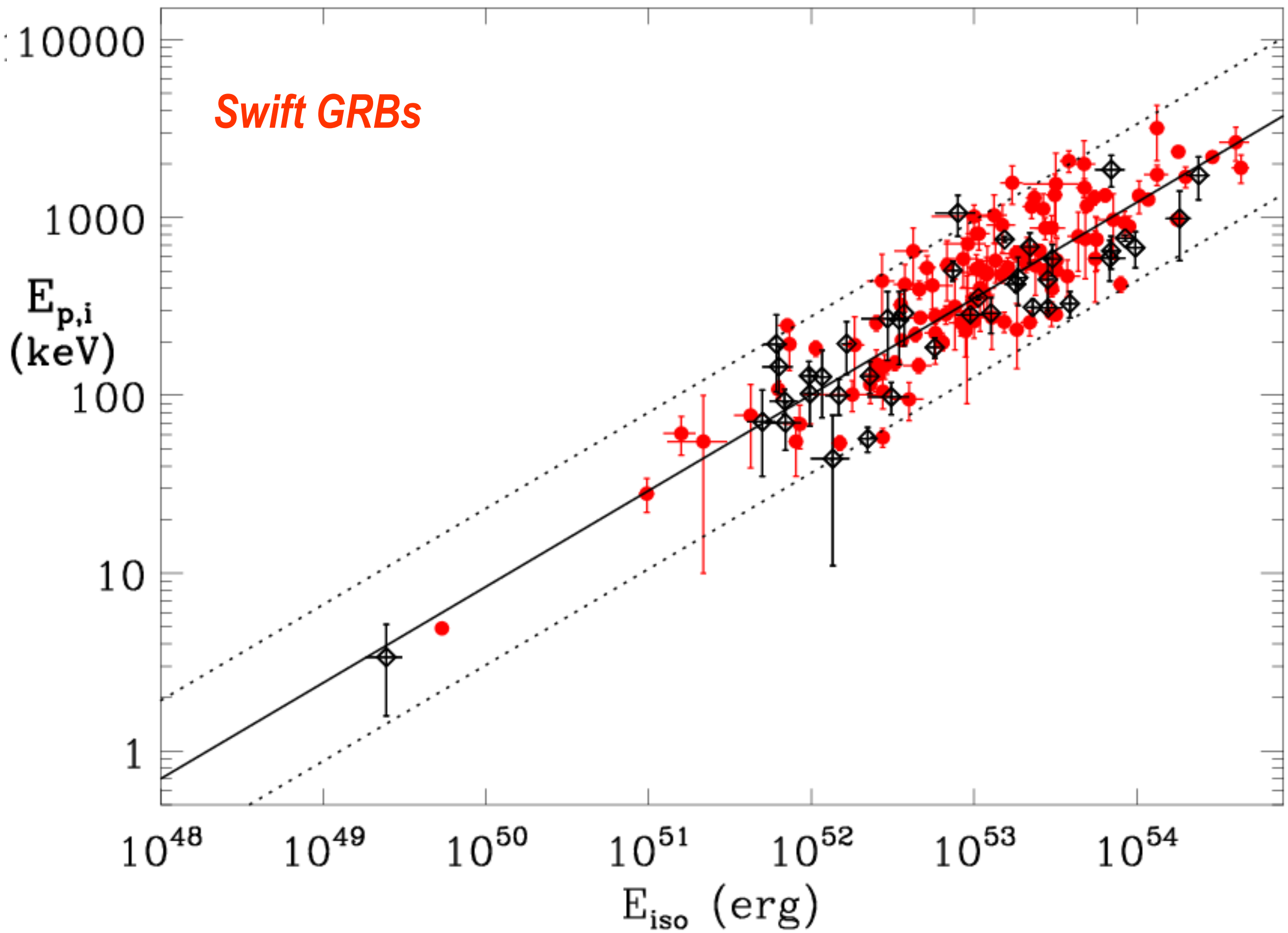
➢ Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities

130 long GRBs as of Sept. 2011



➢ 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

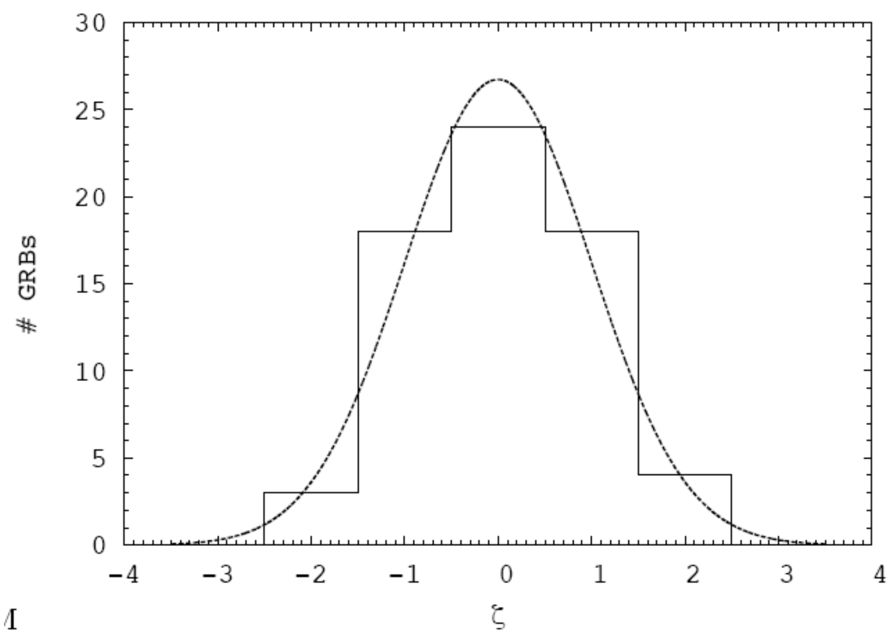


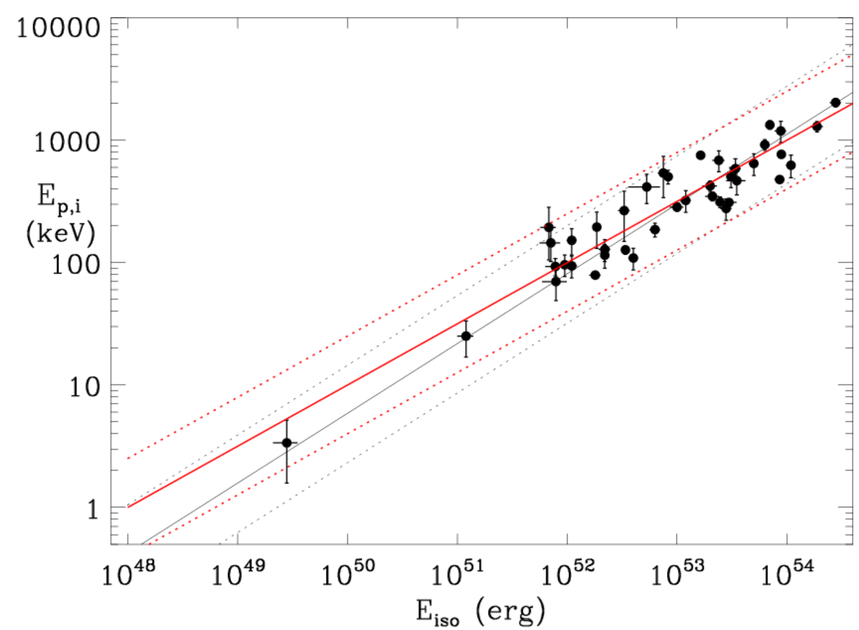
- **strong correlation but significant dispersion** of the data around the best-fit power-law; distribution of residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

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

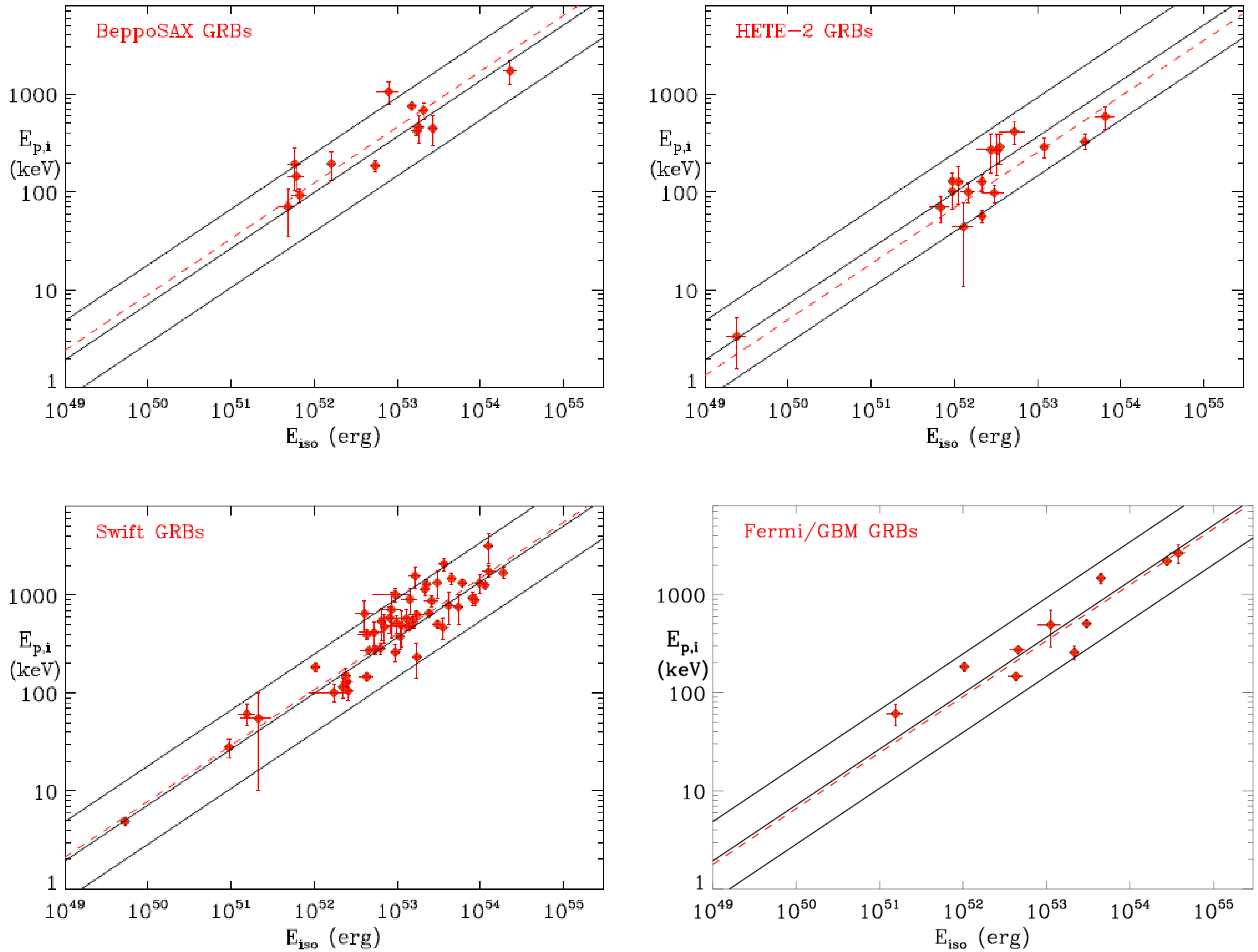
$$L(m, c, \sigma_v ; \boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2}\sum_i \log\left(\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2\right) + \frac{1}{2}\sum_i \frac{(y_i - m\,x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2\,\sigma_{x_i}^2}$$

- with this method Amati et al. (2008, 2009) found an extrinsic scatter σ_{int}(logEp,i) ~ 0.2 and index and normalization t ~0.5 and ~100, respectively

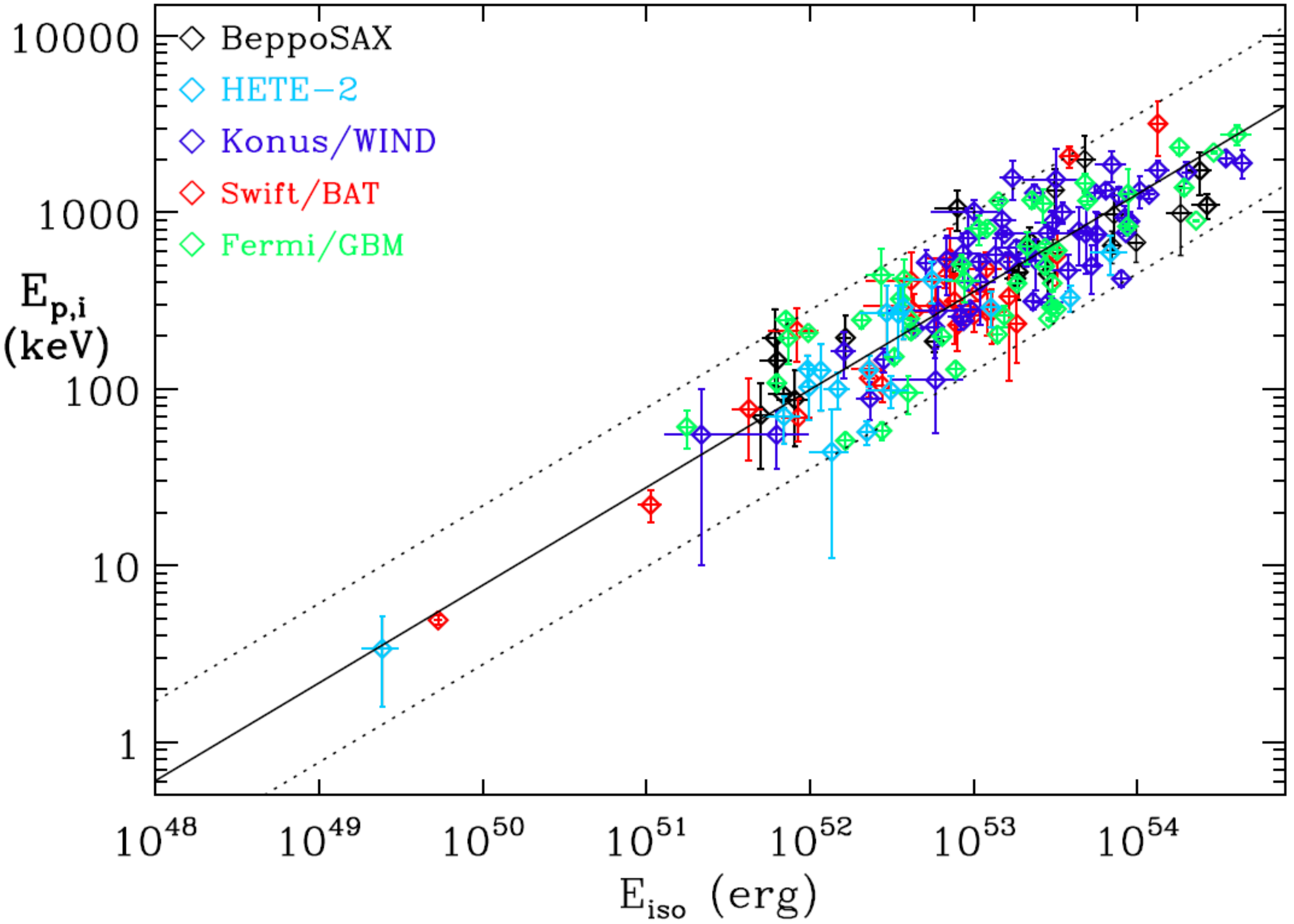




❑ Amati, Frontera & Guidorzi (2009): the normalization of the correlation varies only marginally using measures by individual instruments with different sensitivities and energy bands: **-> no relevant selection effects**



❑ 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**



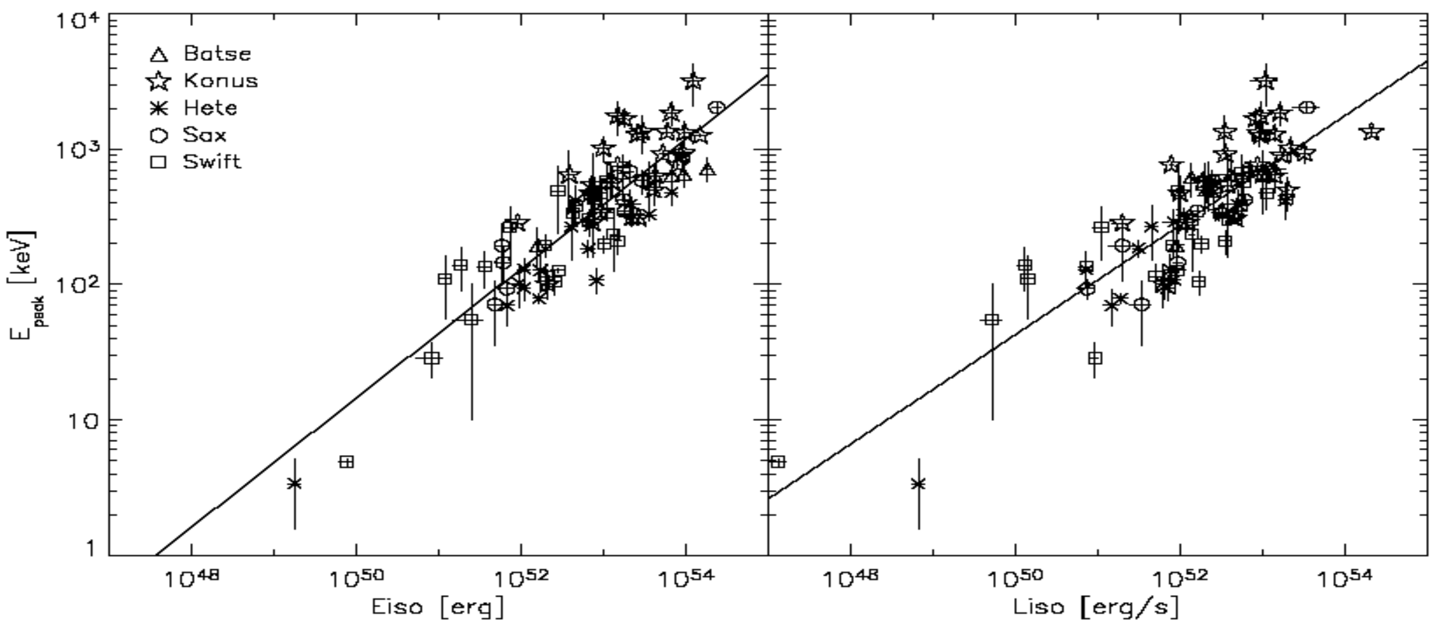
Amati & Della Valle 2013

Correlation of Ep,i with other "intensity" indicators

- the correlation holds also when substituting Eiso with Liso (e.g., Lamb et al. 2004) or Lpeak,iso (Yonetoku et al. 2004, Ghirlanda et al., 2005)

- this is expected because **Liso and Lpeak,iso are strongly correlated with Eiso**

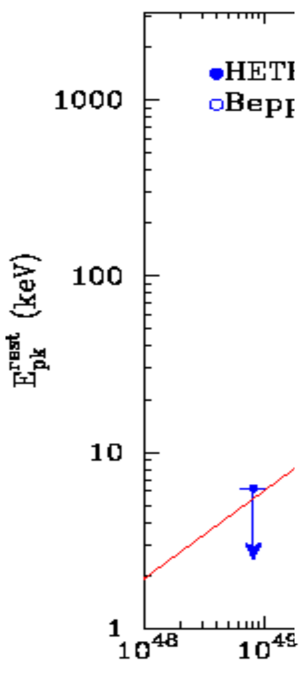
- w/r to Eiso, **Lp,iso is subject to more uncertainties** (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale ?)



Nava et al. 2009

Correlation of Ep,i with other "intensity" indicators

- the correlati ... amb et al. 2004) or Lpeak,iso (Yon...
- this is expec ... **ated with Eiso**
- w/r to Eiso, l ... rves peak at different times ... difficult to estimate; which ...



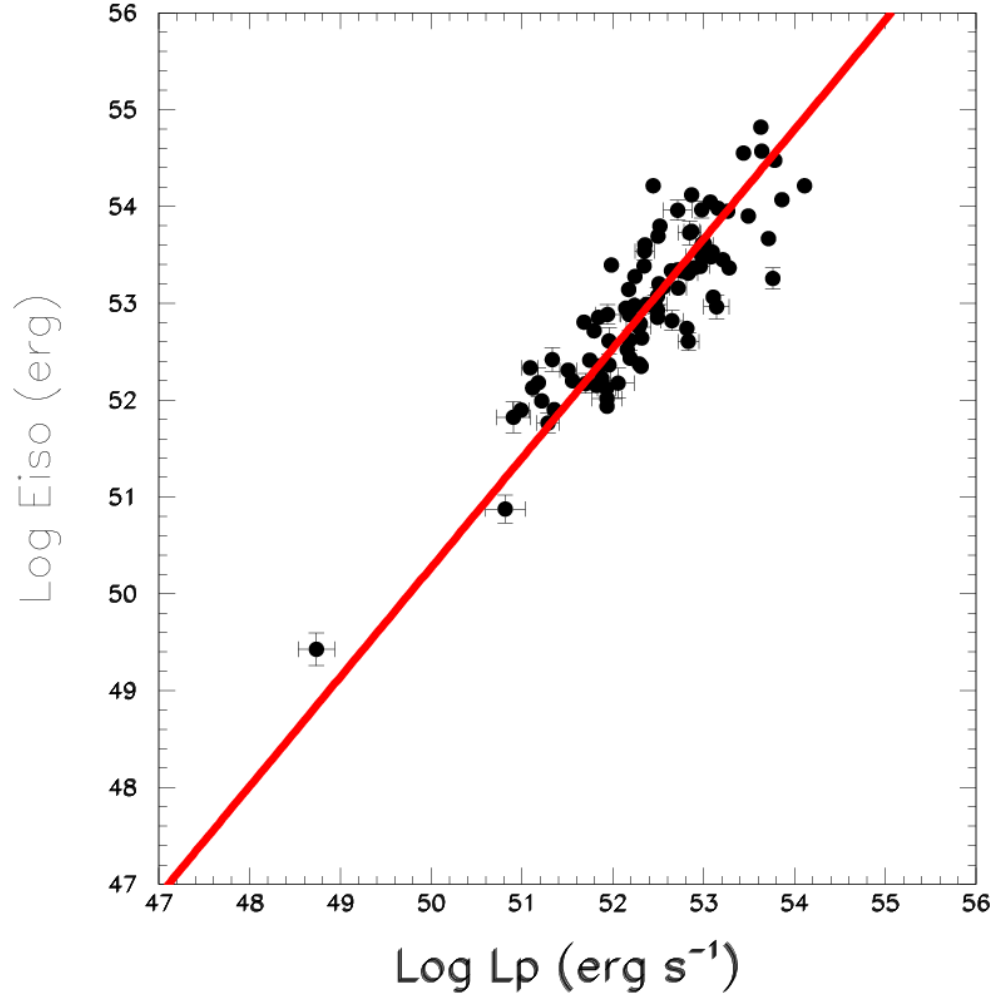
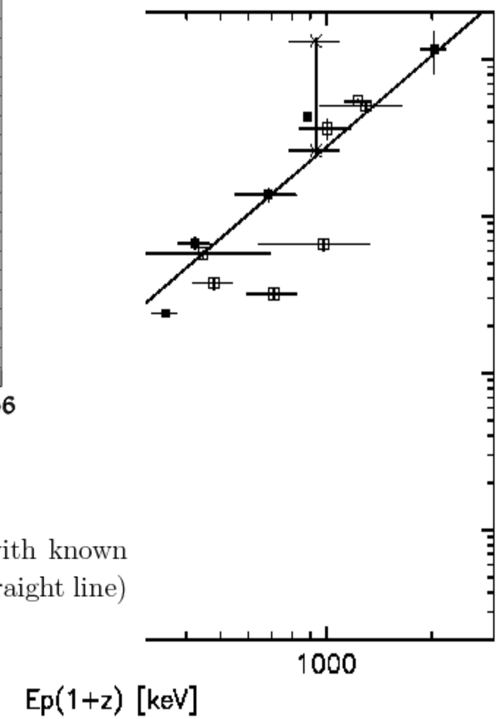


Fig. 3.— The observed correlation between $E_{\gamma,iso}$ and $L_{p,\gamma}$ and for 96 GRBs with known redshift compiled by Yonetoku et al. (2010) The best fit power-law correlation (straight line) has a power-law index 1.13 .

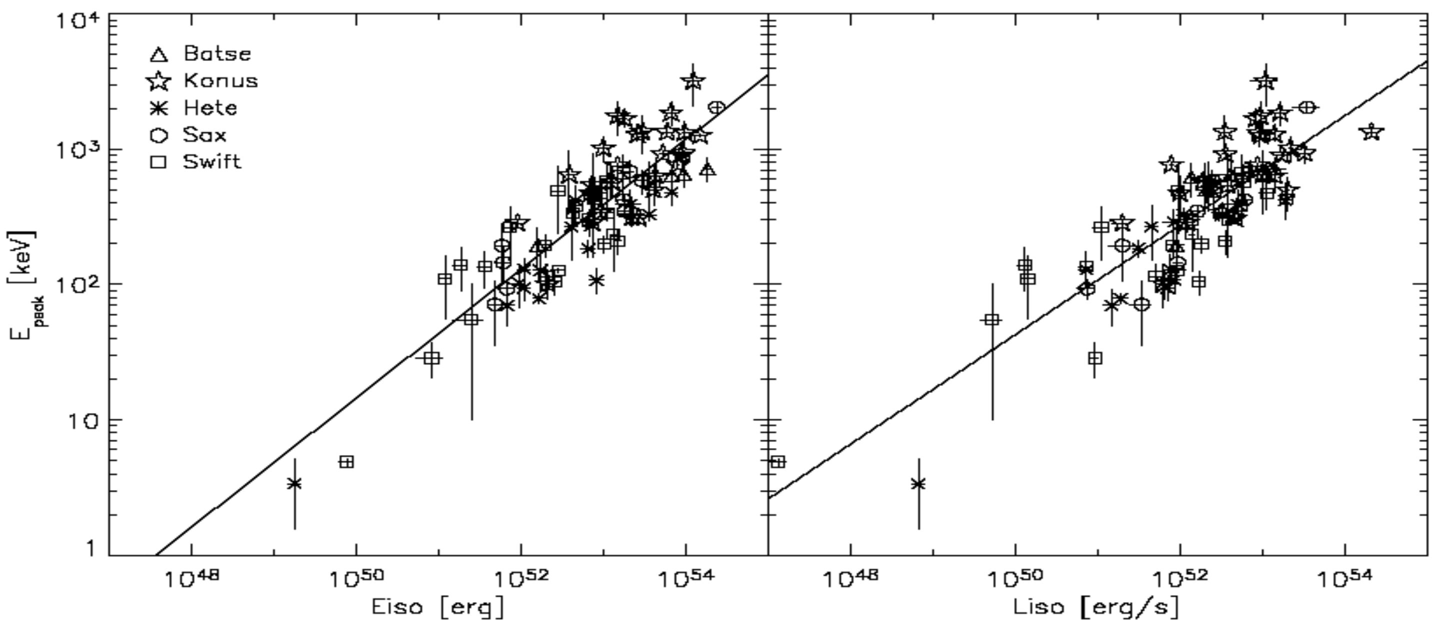


Correlation of Ep,i with other "intensity" indicators

- the correlation holds also when substituting Eiso with Liso (e.g., Lamb et al. 2004) or Lpeak,iso (Yonetoku et al. 2004, Ghirlanda et al., 2005)

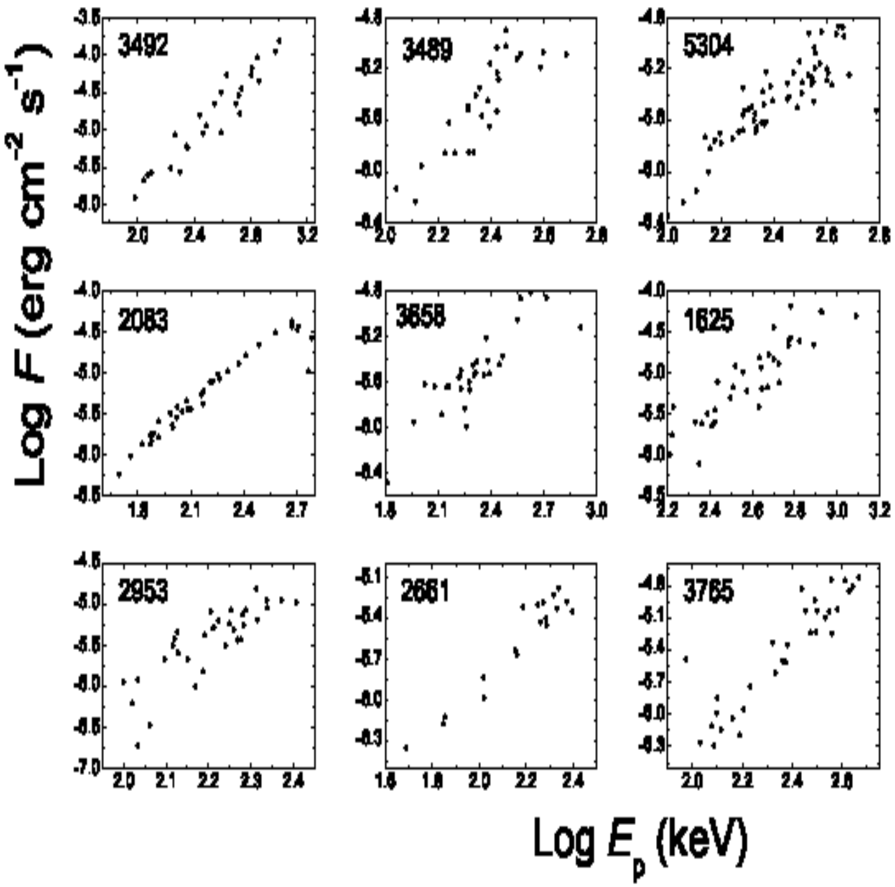
- this is expected because **Liso and Lpeak,iso are strongly correlated with Eiso**

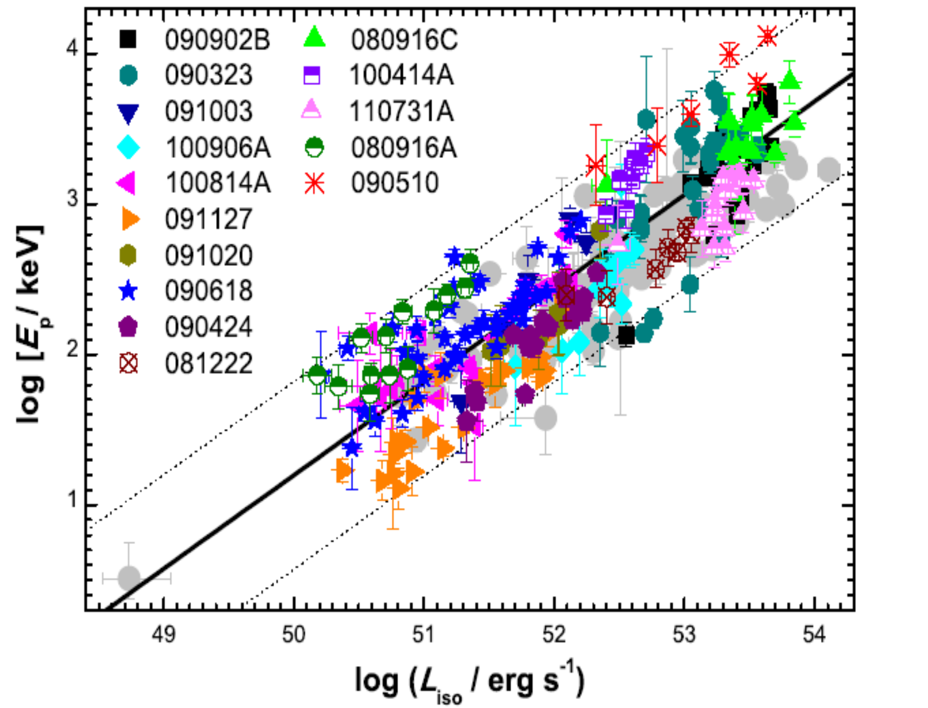
- w/r to Eiso, **Lp,iso is subject to more uncertainties** (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale ?)



Nava et al. 2009

➢ the Ep,i– Liso and Ep,i – Eiso 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**

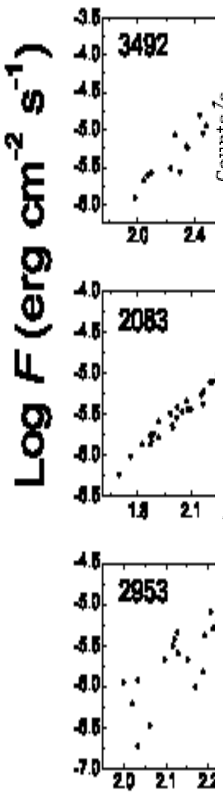


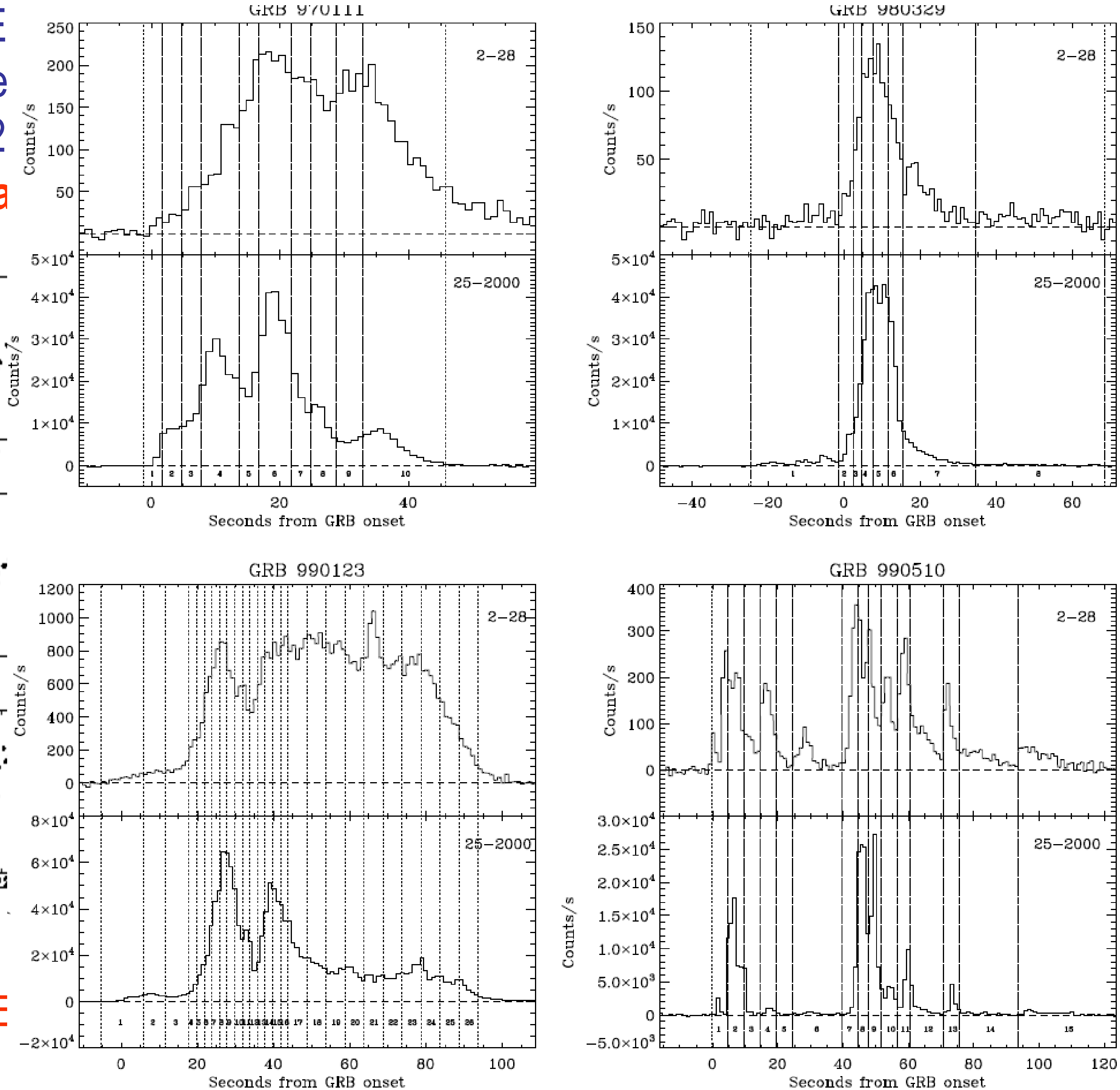


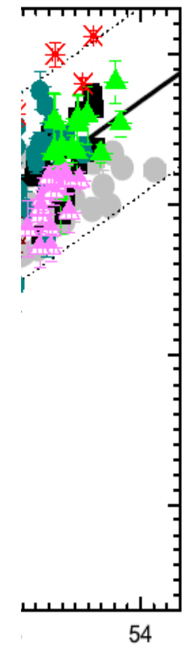
BATSE (Liang et al., ApJ, 2004)

Fermi (e.g., Li et al. , ApJ, 2012)

➢ the E ... on of GRBs (Liang e ... Frontera et al. 2012 ... **lues to explana**

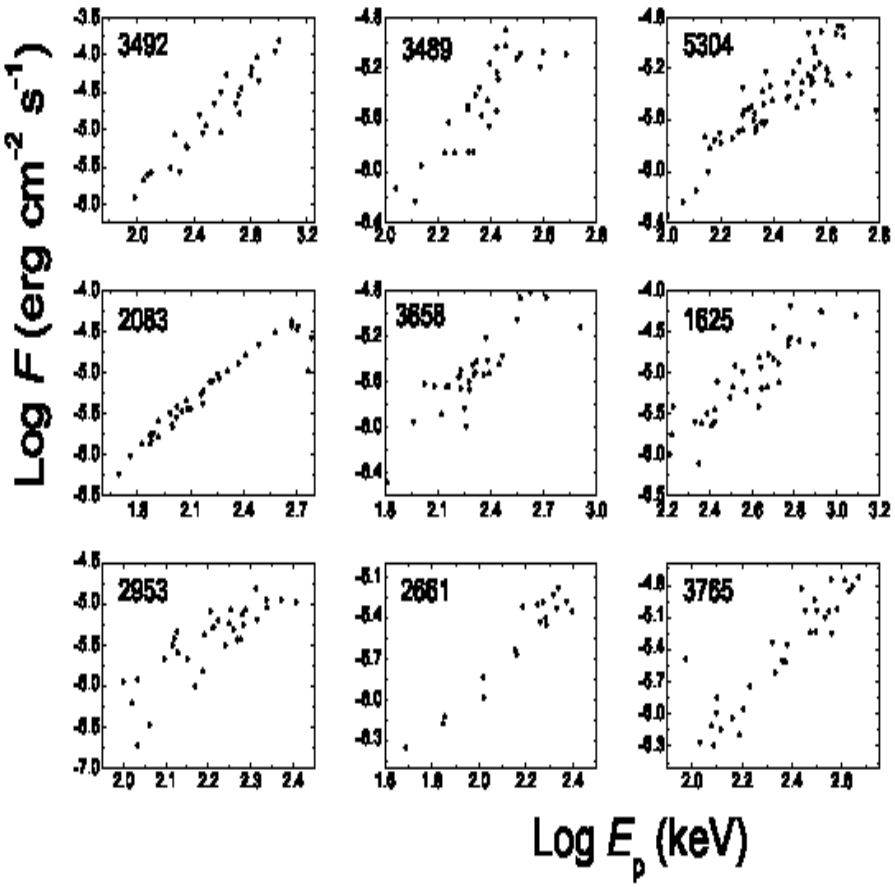




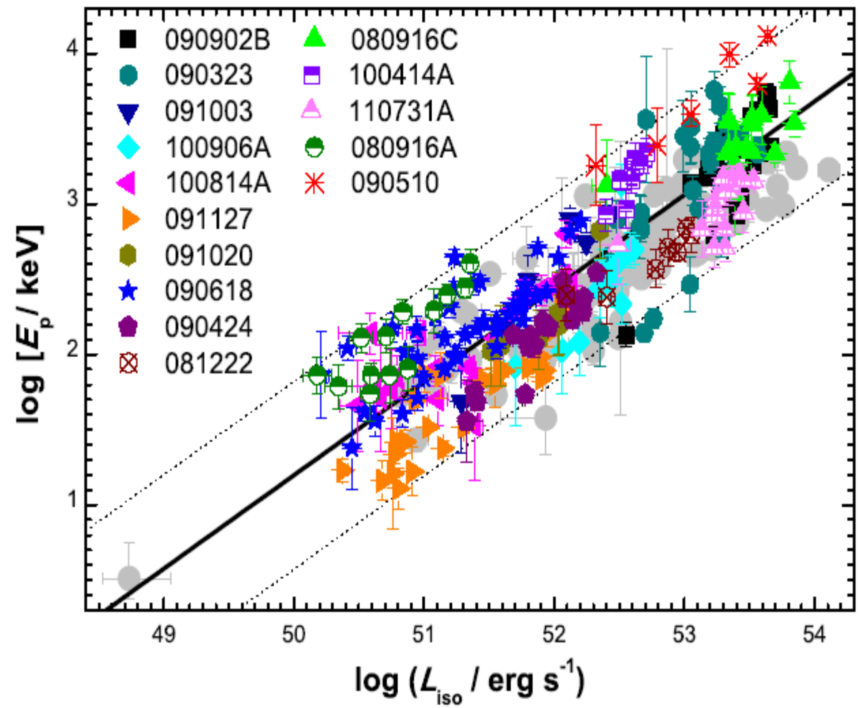


BATSE ... J, 2012)

➢ the Ep,i– Liso and Ep,I – Eiso 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**



BATSE (Liang et al., ApJ, 2004)



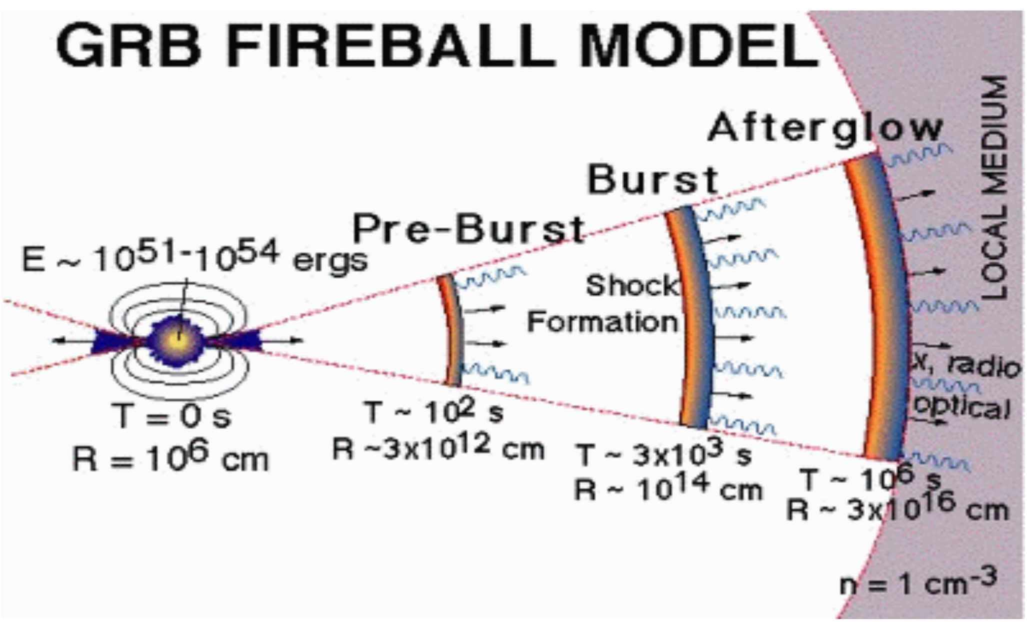
Fermi (e.g., Li et al. , ApJ, 2012)

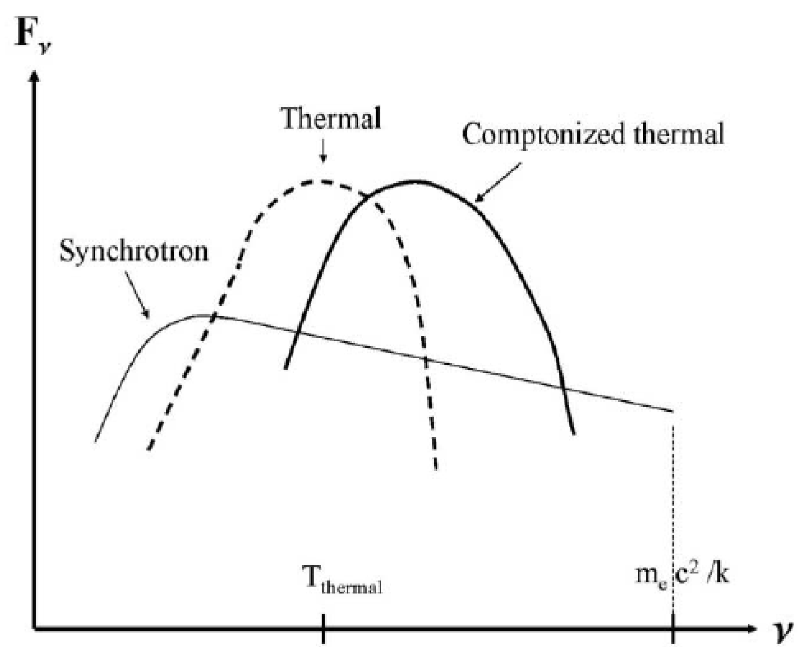
Implications: emission physics and geometry

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

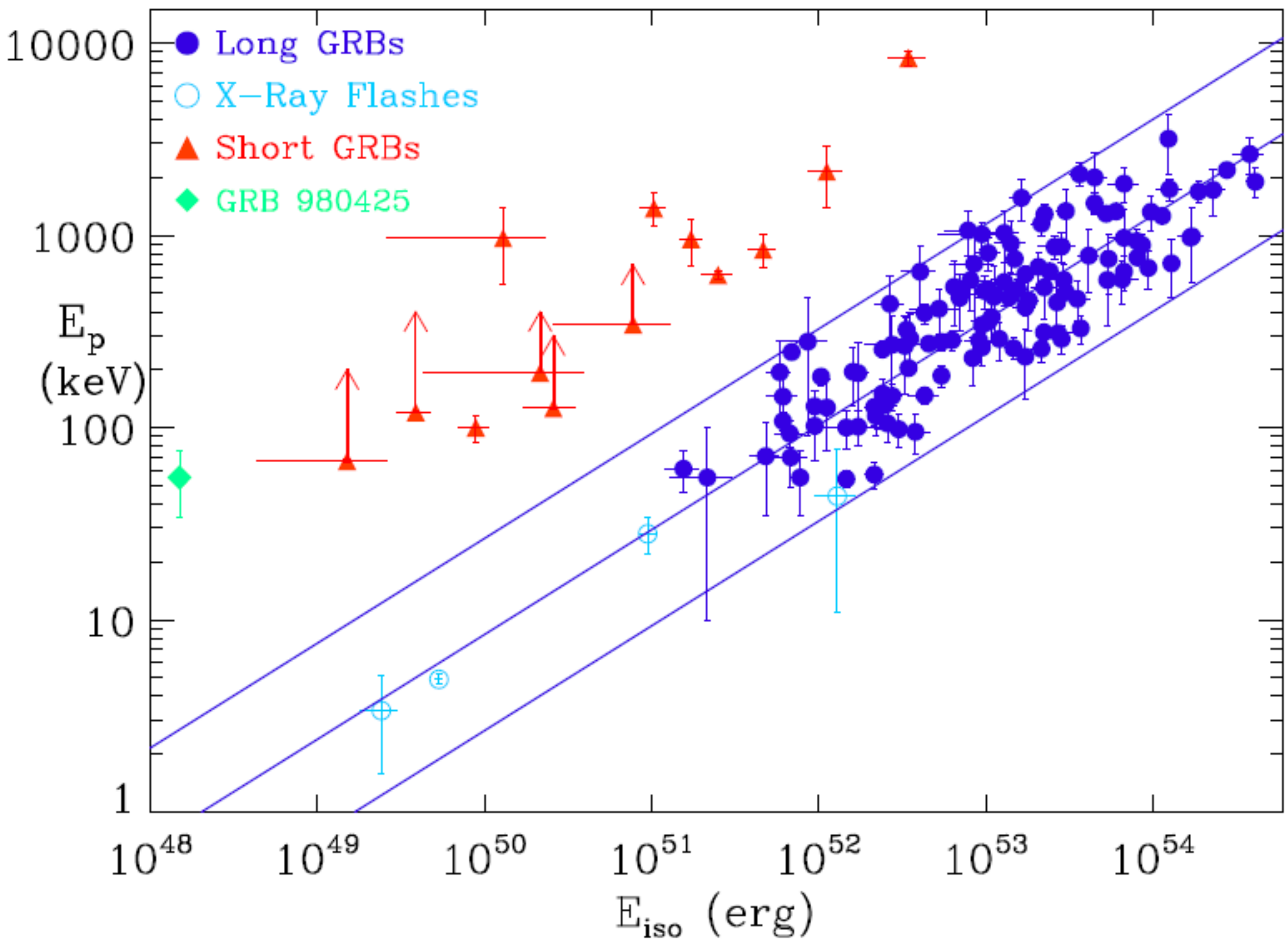
- e.g., $E_p \propto R_0^{-1/2} t_j^{-1/4} E_{\rm iso}^{1/2}$ in scenarios in whch for comptonized thermal emission from the photosphere dominates (e.g. Rees & Meszaros 2005, Thomson et al. 2006)





➢ *Implications: sub-classes of GRBs*

➢ Up to date (Sept. 2012) Ep,i – Eiso plane: 148 long GRBs, 4 XRFs, 13 short GRBs



"Standardizing" GRB with the Ep,i - Intensity correlation

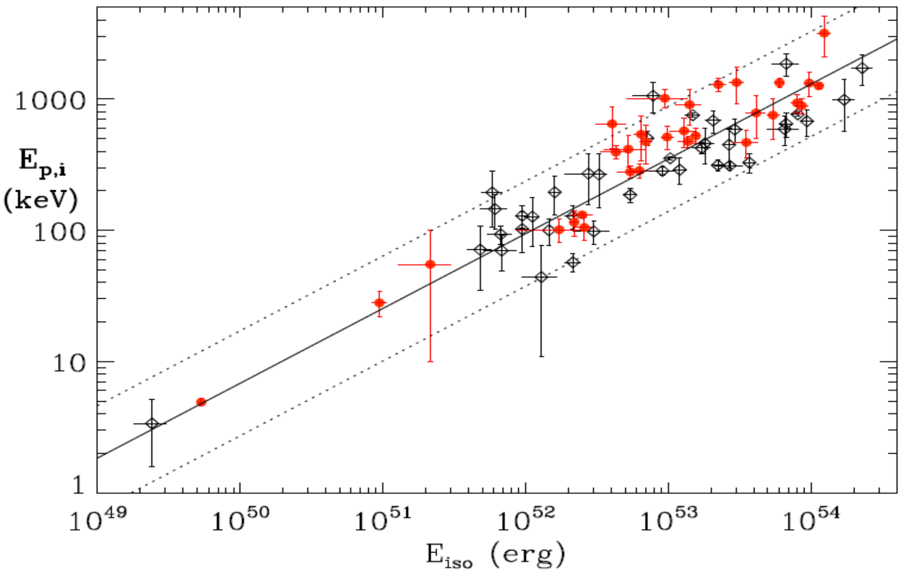
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

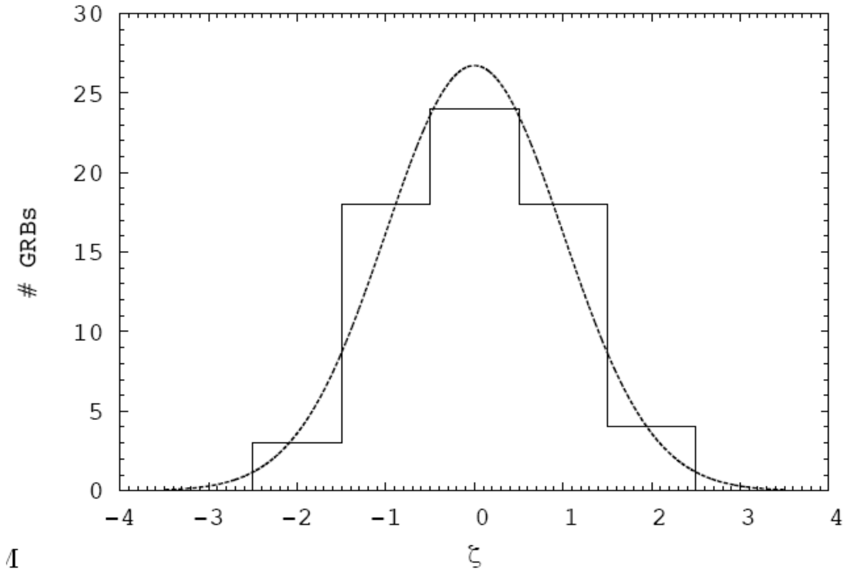
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\, N(E)\, dE \quad \text{erg}$$

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

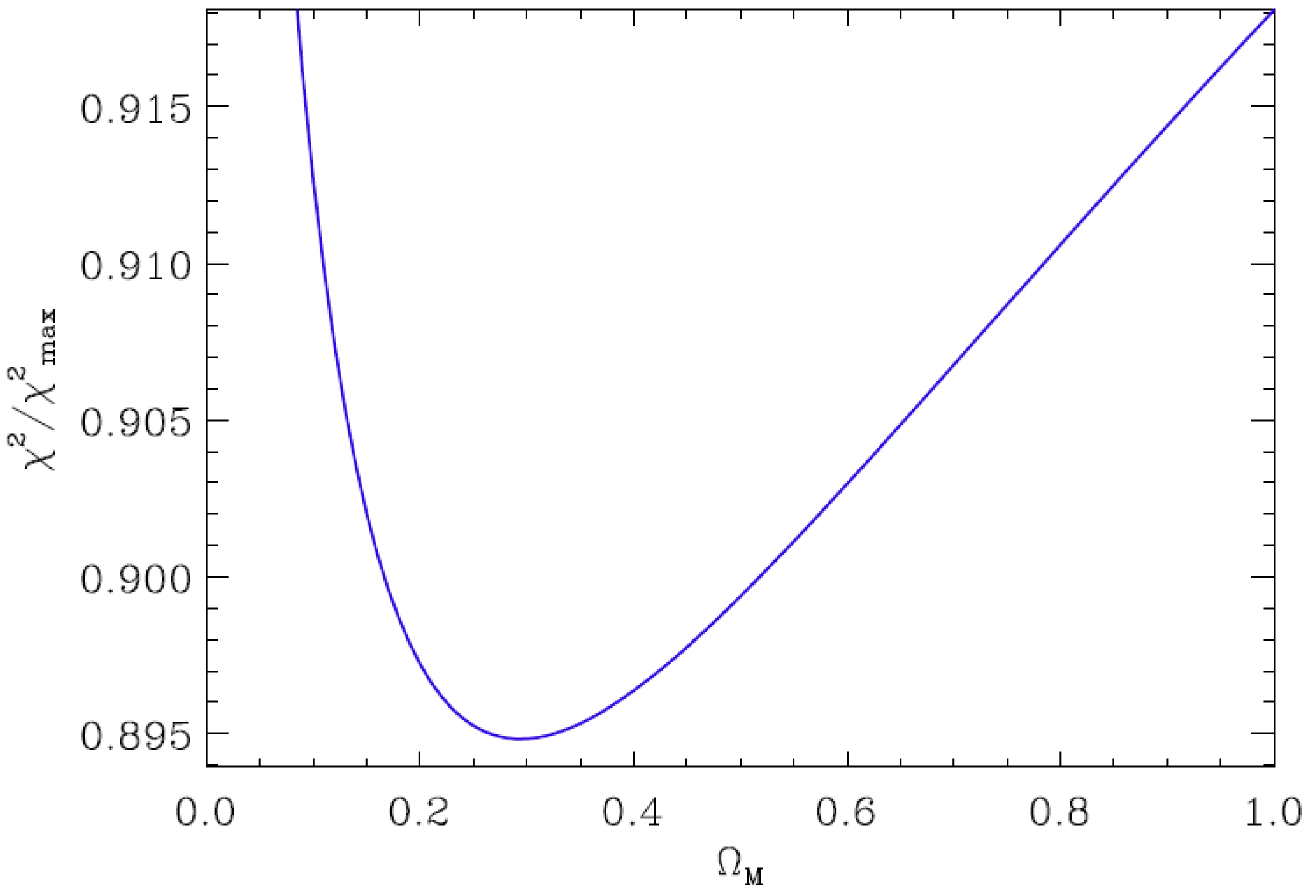
- not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters

- 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 ΛCDM universe , Ω_M is lower than 1 and around 0.3

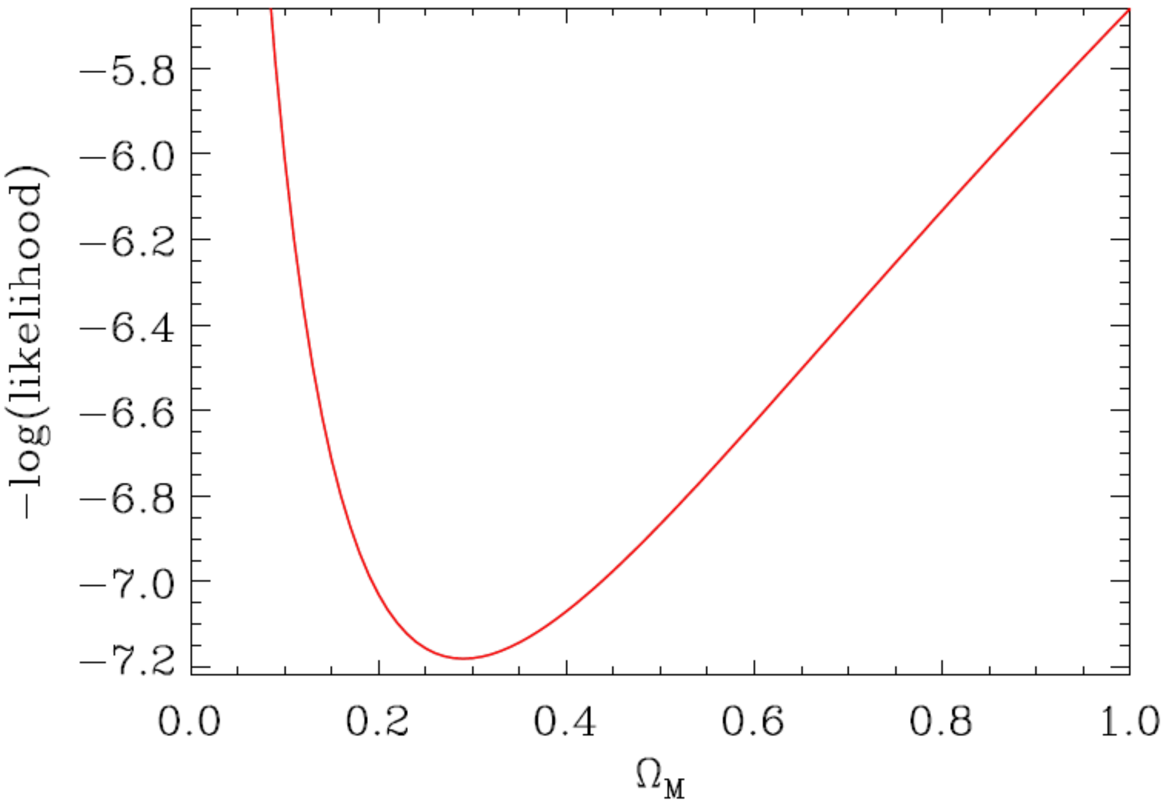


Amati et al. 2008, Amati & Della Valle 2013

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

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

- Ω_M could be constrained (Amati+08, 70 GRBs) to 0.04-0.43 (68%) and 0.02-0.71 (90%) for a flat ΛCDM universe (Ω_M = 1 excluded at 99.9% c.l.)

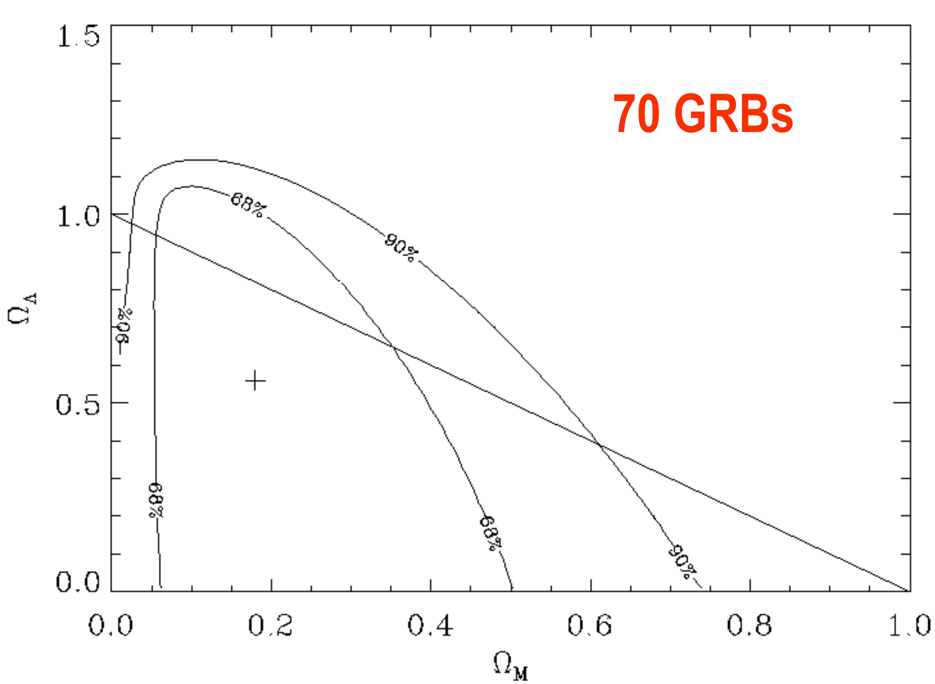


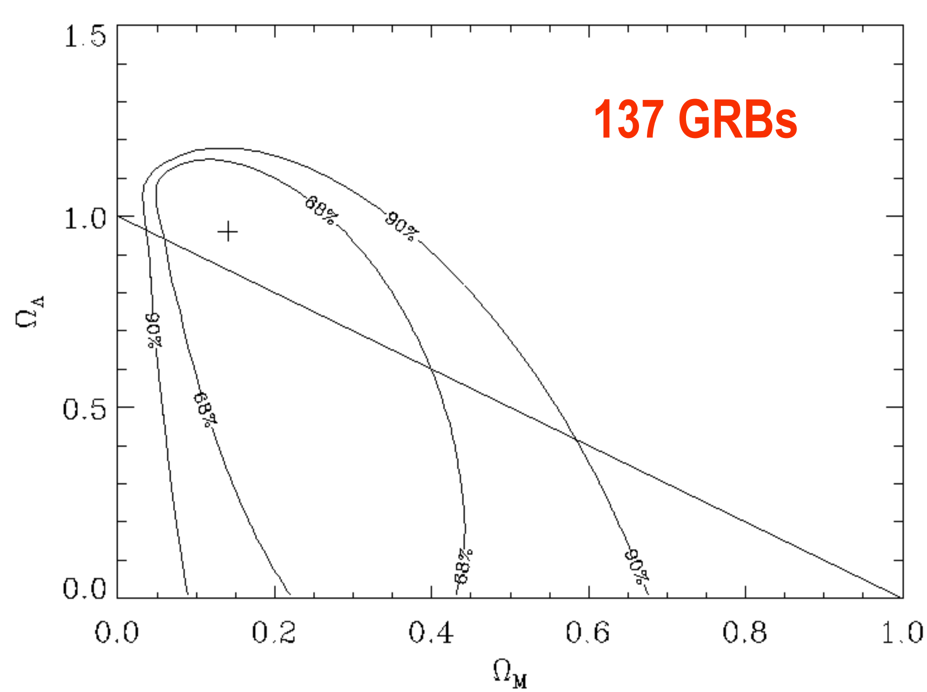
Amati et al. 2008, 2013

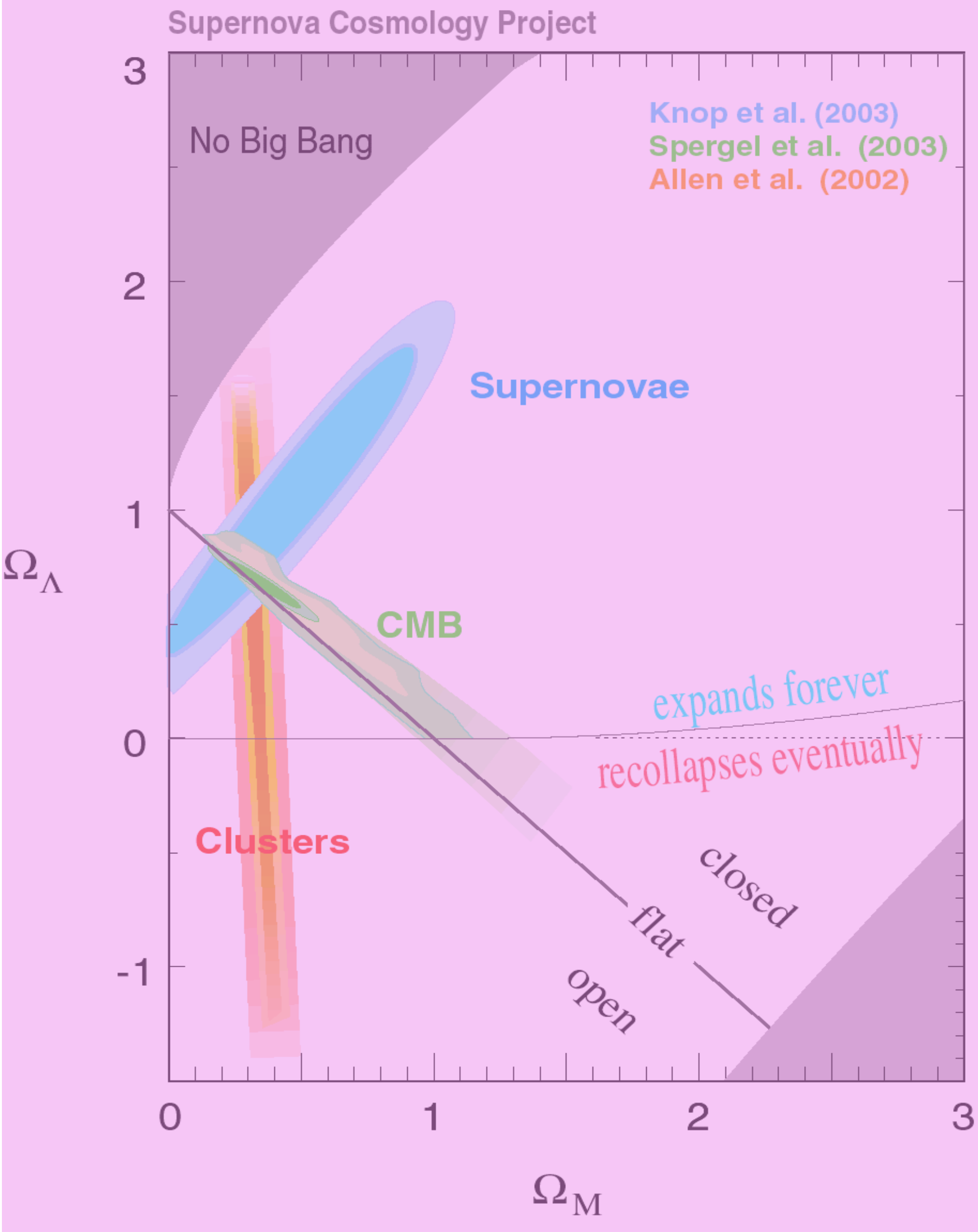
➢ analysis of updated sample of 137 GRBs (Amati+12) shows significant improvements w/r to the sample of 70 GRBs of Amati et al. (2008)

➢ this evidence supports the reliability and perspectives of the use of the Ep,i – Eiso correlation for the estimate of cosmological parameters

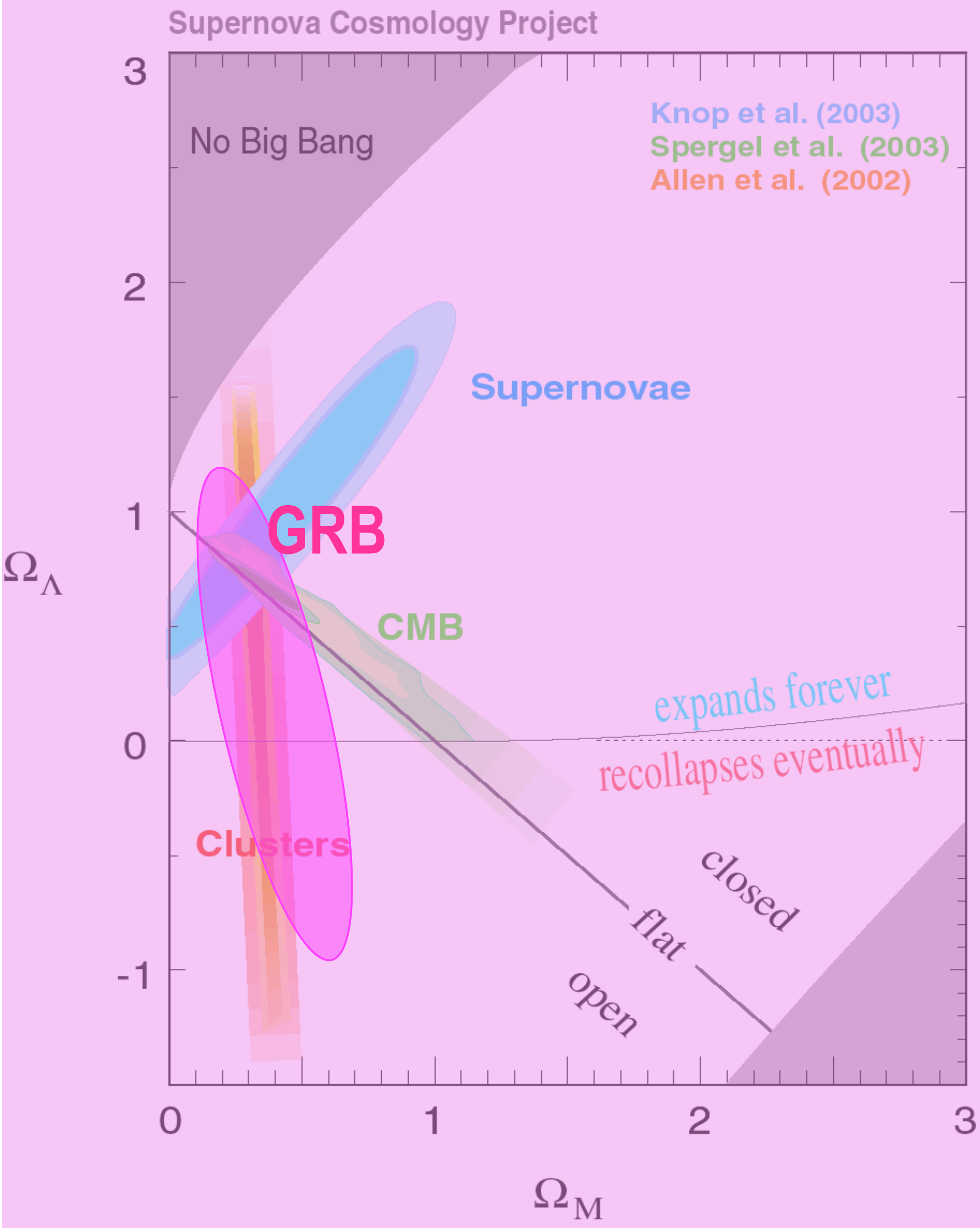
Ωm (flat universe)	best	*68%*	*90%*
70 GRBs (Amati+ 08)	0.27	0.09 – 0.65	0.05 – 0.89
137 GRBs (Amati+ 12)	0.29	0.12 – 0.54	0.08 – 0.79







Supernova Cosmology Project
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
No Big Bang
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3



Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
GRB
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
Ω_Λ
Ω_M
3
2
1
0
-1
0
1
2
3

Perspectives

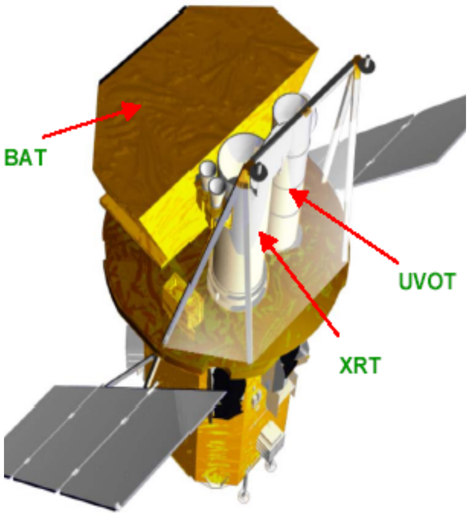
❑ **present and near future: main contribution expected from joint Fermi + Swift measurements**

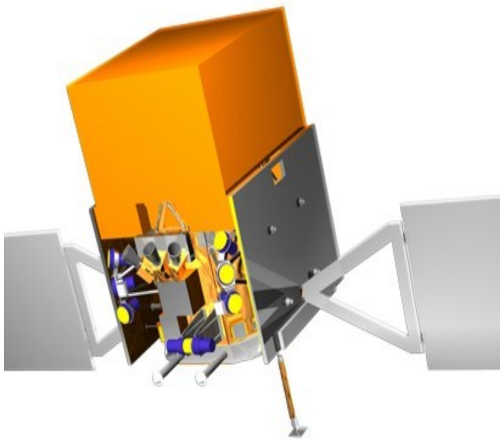
➢ Up to 2009: ~290 Fermi/GBM GRBs, Ep estimates for ~90%, ~35 simultaneously detected by Swift (~13%), 13 with **Ep and z** estimates **(~10% of Swift sample)**

➢ 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**





Perspectives

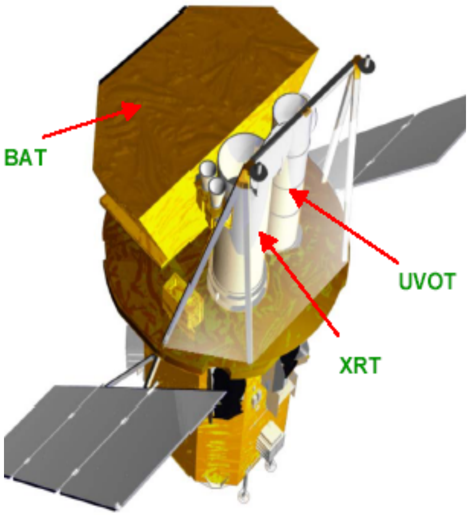
❑ **present and near future: main contribution expected from joint Fermi + Swift measurements**

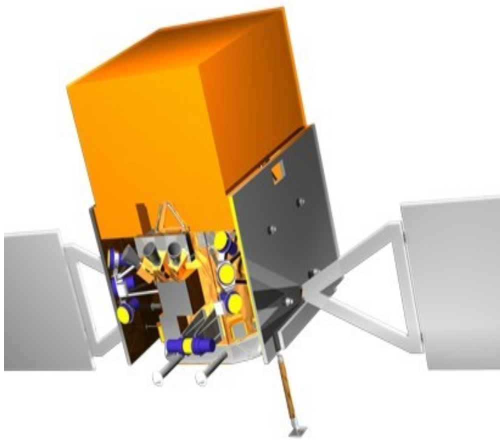
➢ Up to 2009: ~290 Fermi/GBM GRBs, Ep estimates for ~90%, ~35 simultaneously detected by Swift (~13%), 13 with **Ep and z** estimates **(~10% of Swift sample)**

➢ 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**





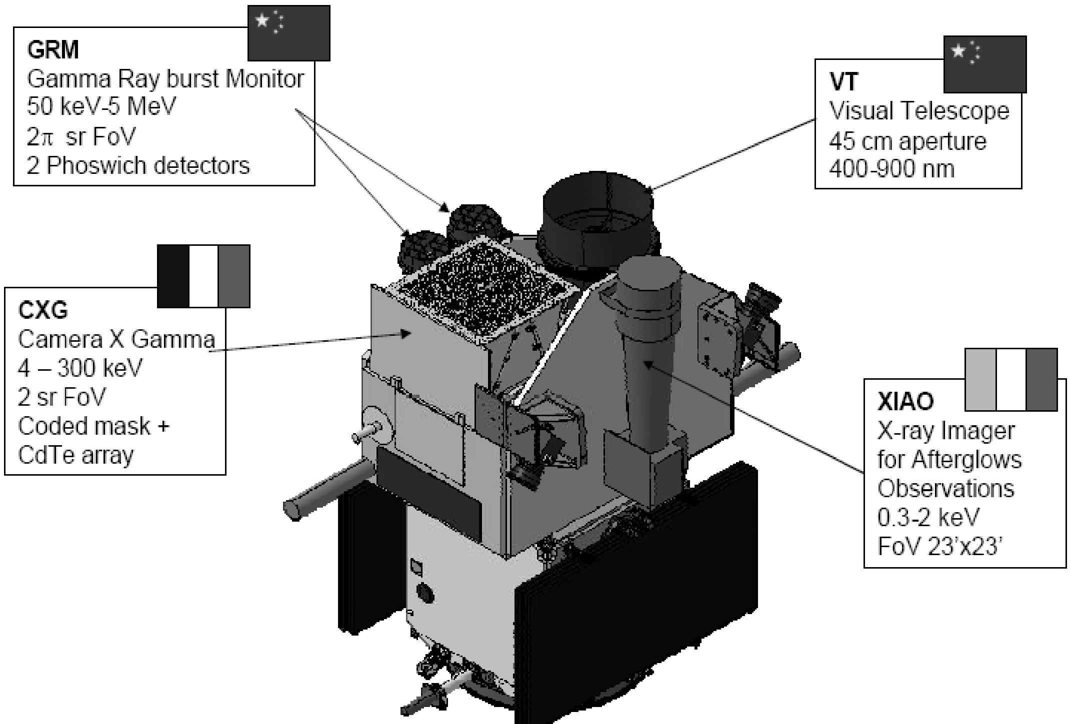
❑ In the > 2015 time frame a significant step forward expected from SVOM, UFFO, CALET/GBM, LOFT/WFM

- spectral study of prompt emission in 5-5000 keV -> accurate estimates of Ep 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

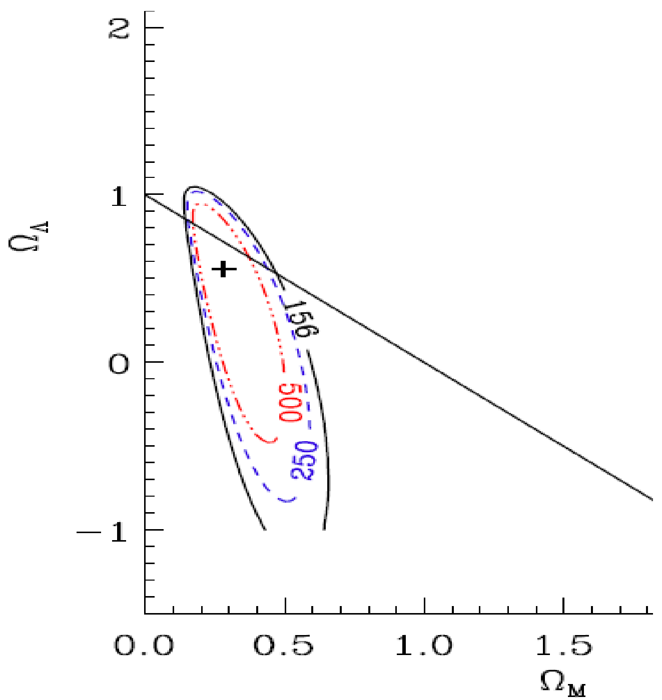
- substantial increase of the number of GRB with known z and Ep -> test of correlations and calibration for their cosmological use



❑ Expected significant enlargement of the sample in a few years

- the simulatenous 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 (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)

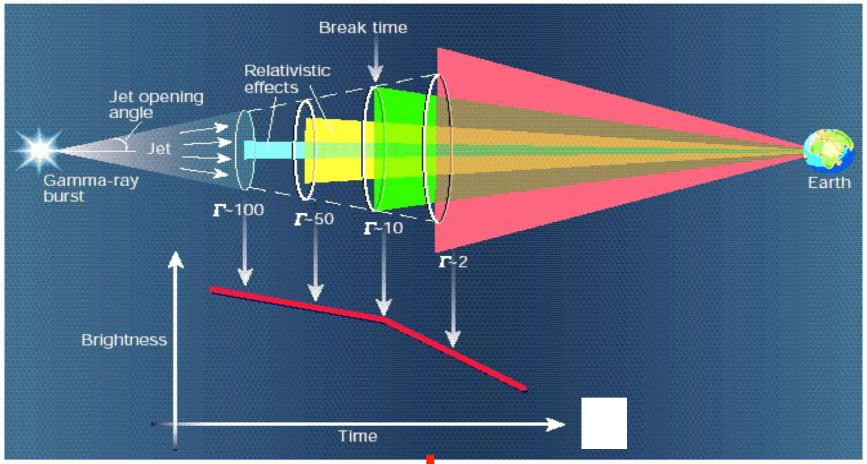
GRB #	Ω_M (flat)
70 (real) GRBs (Amati+ 08)	$0.27^{+0.38}_{-0.18}$
156 (real) GRBs (Amati+ 13)	$0.29^{+0.28}_{-0.15}$
250 (156 real + 94 simulated) GRBs	$0.29^{+0.16}_{-0.12}$
500 (156 real + 344 simulated) GRBs	$0.29^{+0.10}_{-0.09}$



Amati & Della Valle 2013

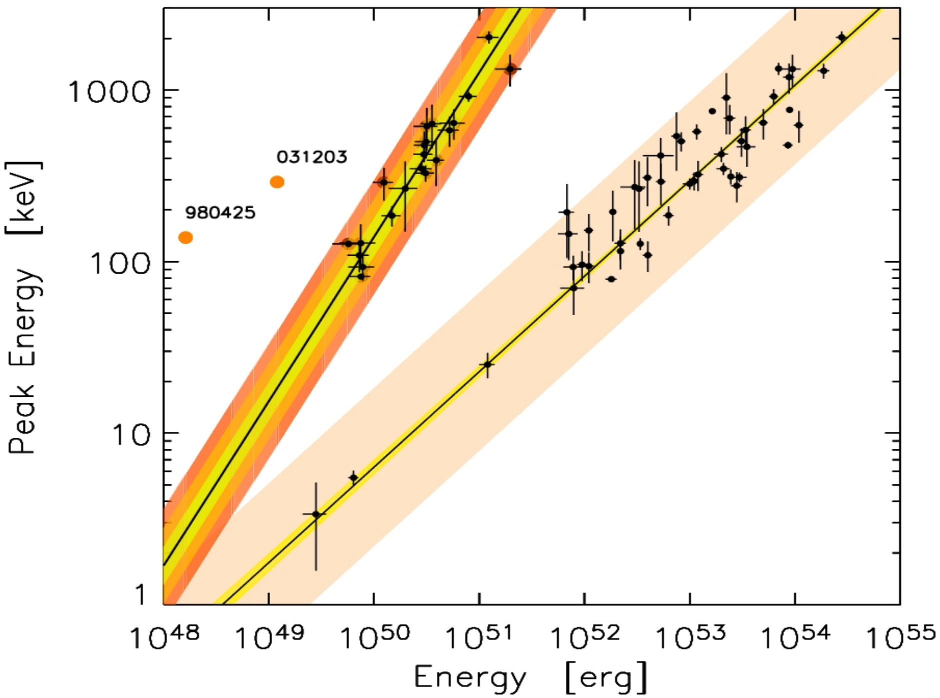
❑ Accounting for collimation

➢ 2004: evidence that by substituting Eiso with the collimation corrected energy Eγ 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)



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

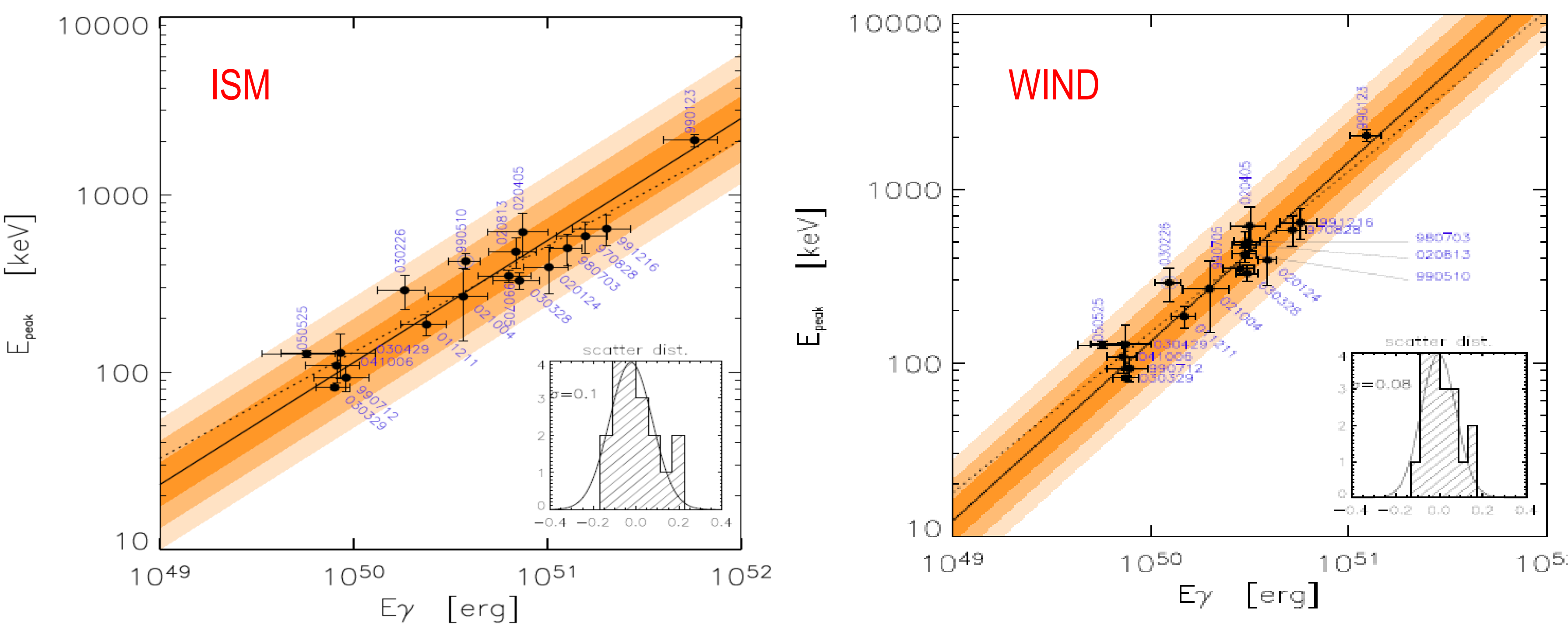
$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$



❑ Accounting for collimation: drawbacks

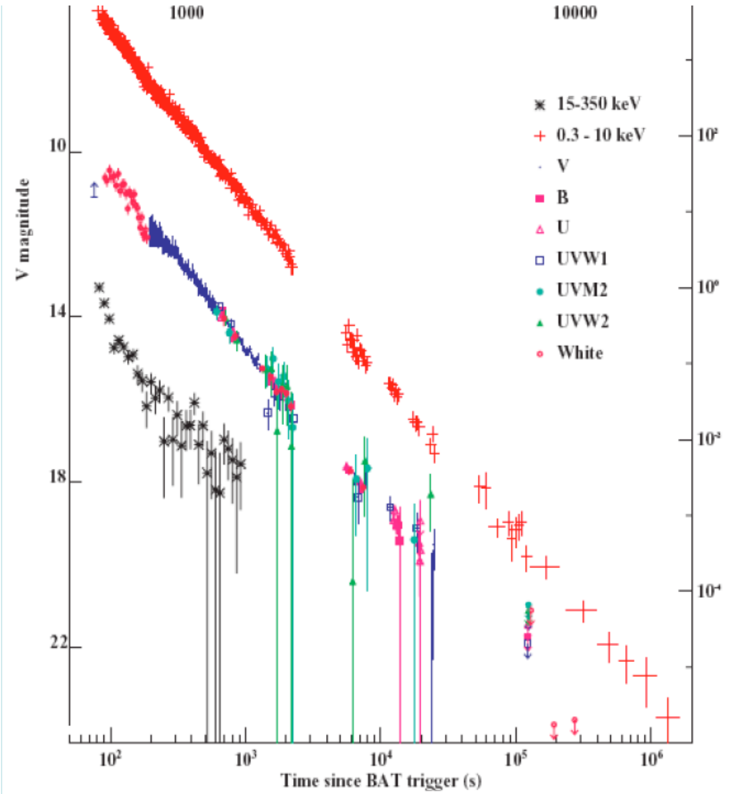
➢ the Ep-Eγ correlation is model dependent: slope depends on the assumptions on the circum-burst environment density profile (ISM or wind)

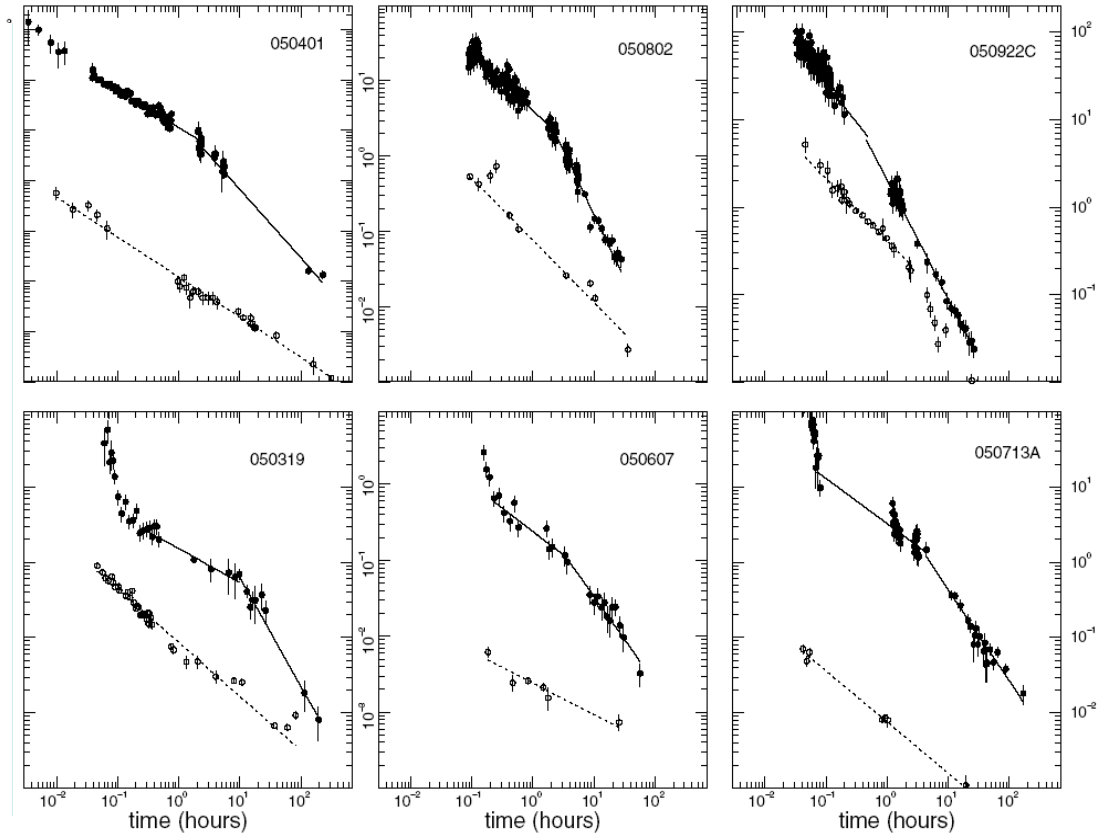
➢ **addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions) and substantially reduces the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)



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 ?



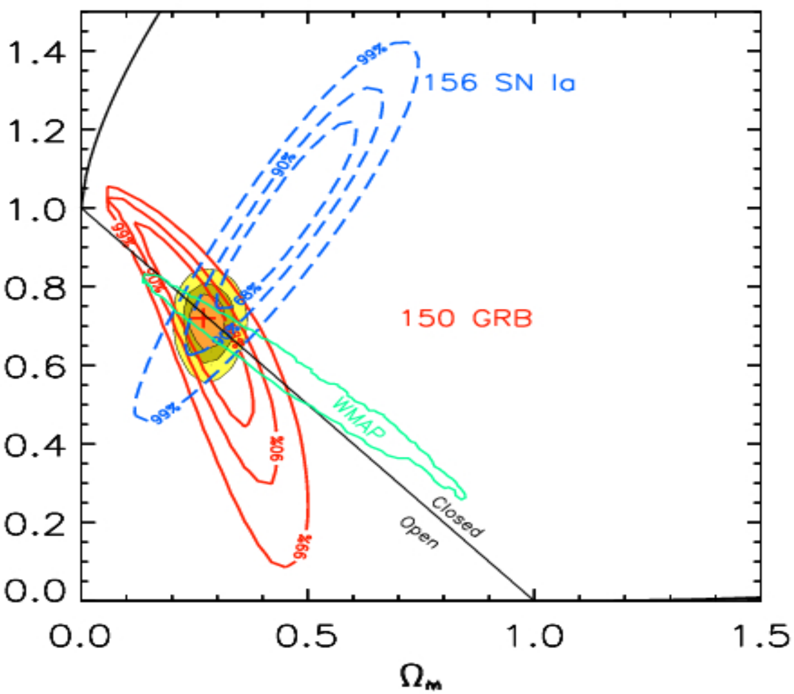


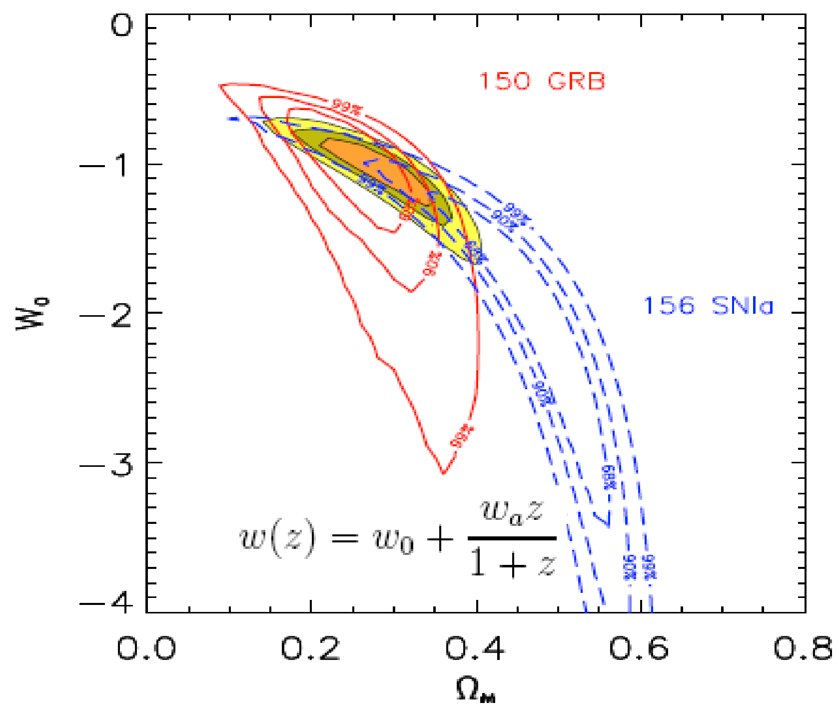
- **Addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions **and substantially reduces the number of GRB that can be used (e.g., #$E_{p,i} - E_\gamma$ ~ ¼ #$E_{p,i} - E_{iso}$)**

- **Amati et al. 2008 (and many others afterwards): let's make a step backward and focus on the "simple" Ep,i – Eiso (Ep,i - Liso) correlation**

❑ Accounting for collimation: perspectives

- the simulatenous 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 reliable estimates of jet opening angles and structure (e.g., via radio measurements by SKA) would improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)





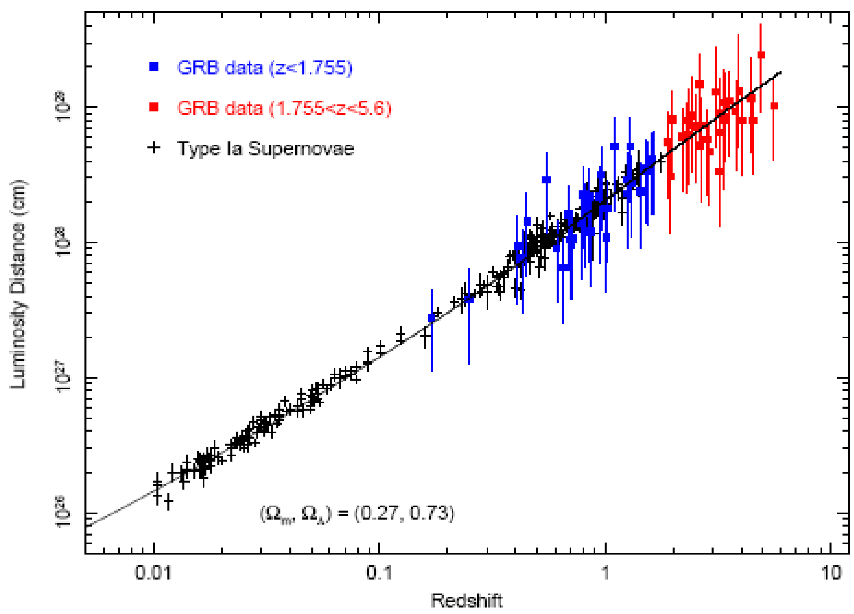
Adapted from Ghirlanda+ 2007

❑ Calibrating the Ep,i – Eiso correlation with SN Ia

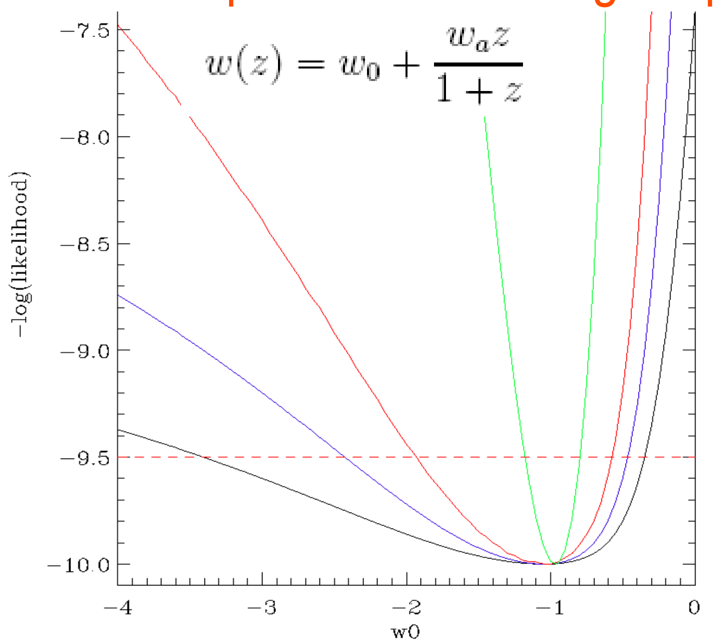
➢ Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at z < 1.7 by using the luminosity distance – redshift relation derived for SN Ia

➢ The aim is to extend the SN Ia Hubble diagram up to redshifts at which the luminosity distance is more sensitive to dark energy properties and evolution

➢ Drawback: with this method GRB are no more an indipendent cosmological probe



Kodama et al. 2008



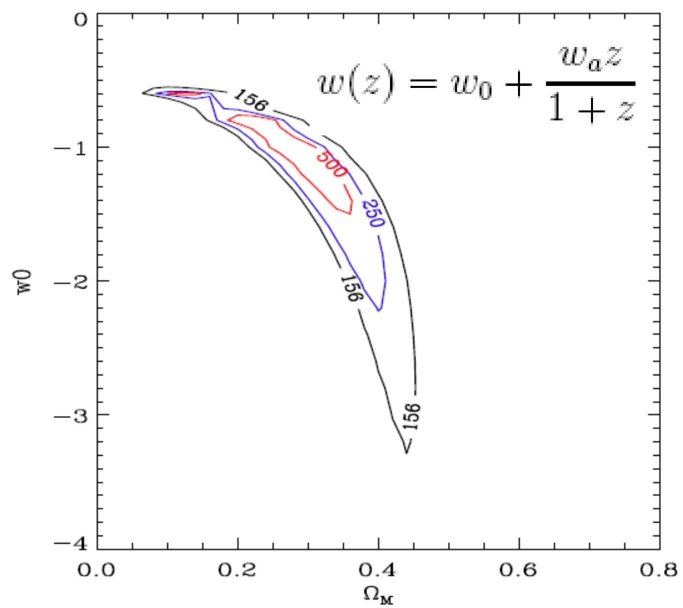
Amati & Della Valle 13, Amati+ 13

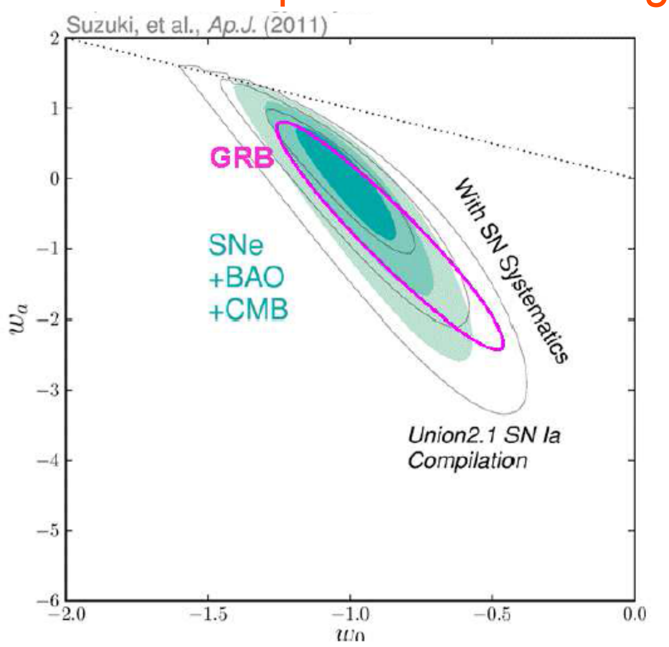
❑ Calibrating the Ep,i – Eiso correlation with SN Ia

➢ 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 redshifts at which the luminosity distance is more sensitive to dark energy properties and evolution

➢ Drawback: with this method GRB are no more an indipendent cosmological probe

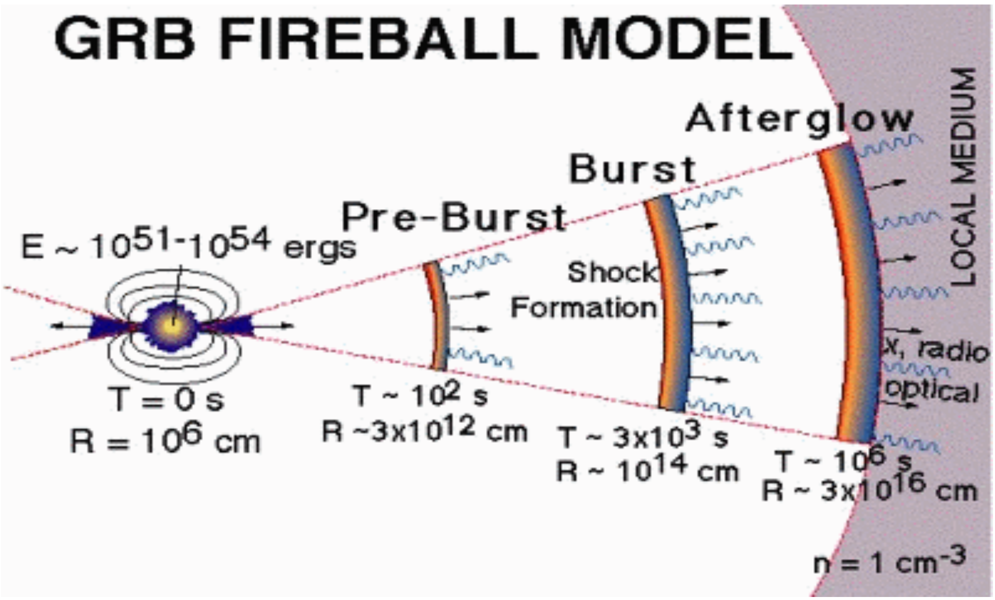


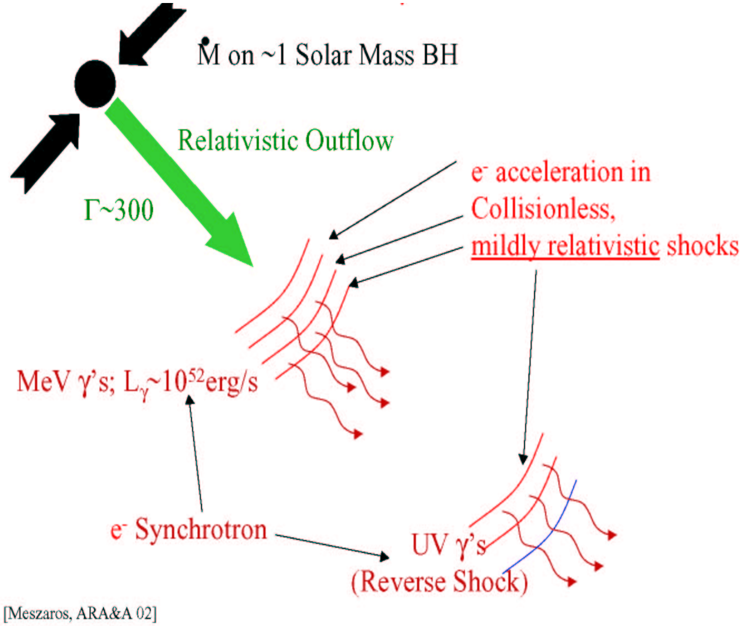


Amati & Della Valle 2013, Amati+ 2013

❑ Understanding the physical grounds of the correlation

➢ **Ep is a fundamental parameter in GRB prompt emission models**





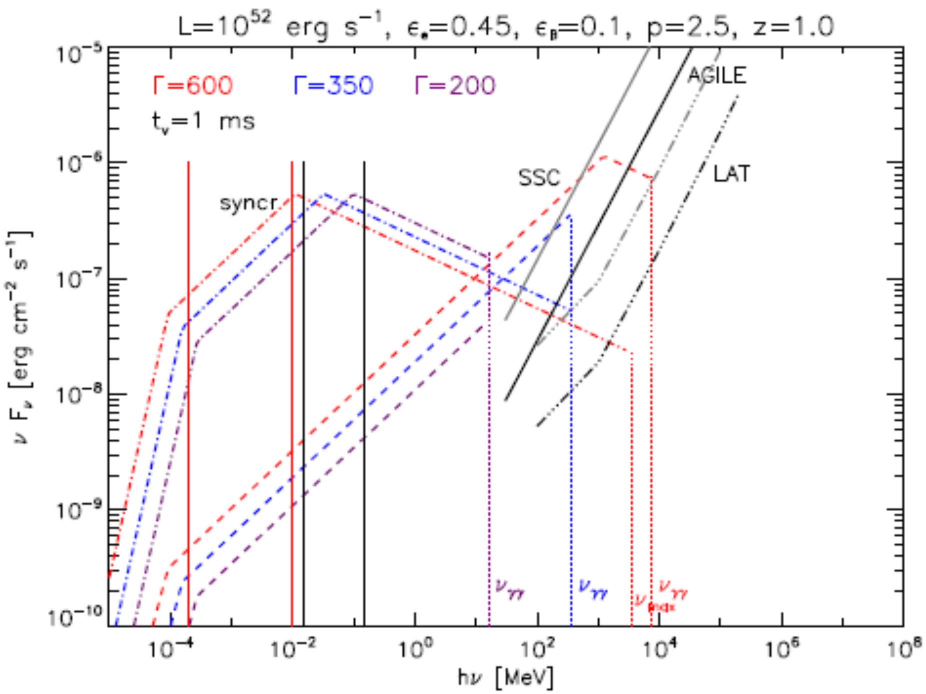
➢ ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)

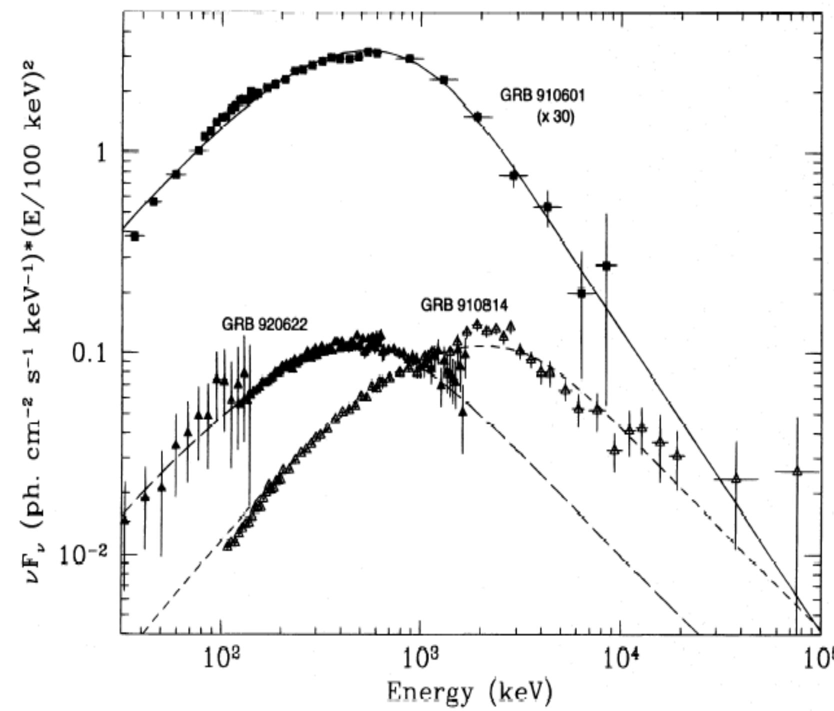
➢ non thermal spectra -> shocks synchrotron emission (SSM)

➢ 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 ν_m in fast cooling regime) or to the temperature of the Maxwellian distribution of the emitting electrons

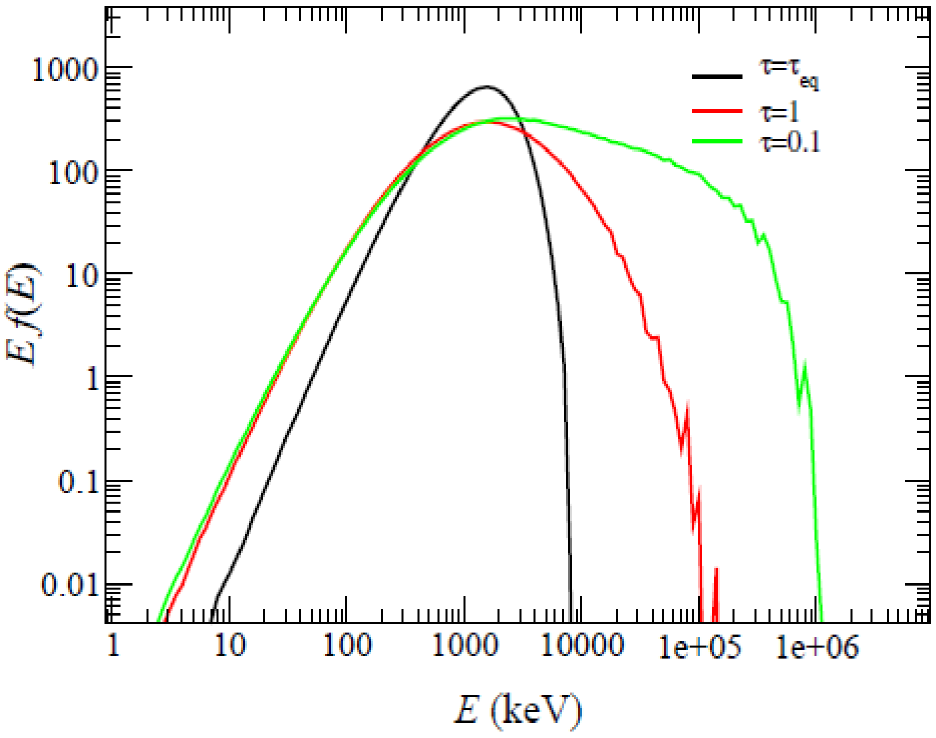


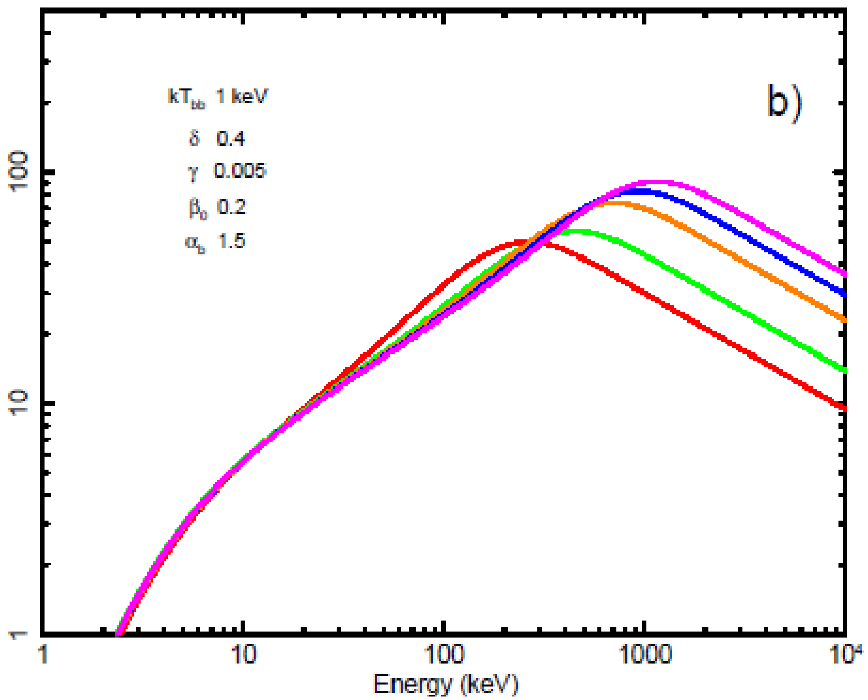


Galli & Guetta 2007

Tavani, ApJ, 1995

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



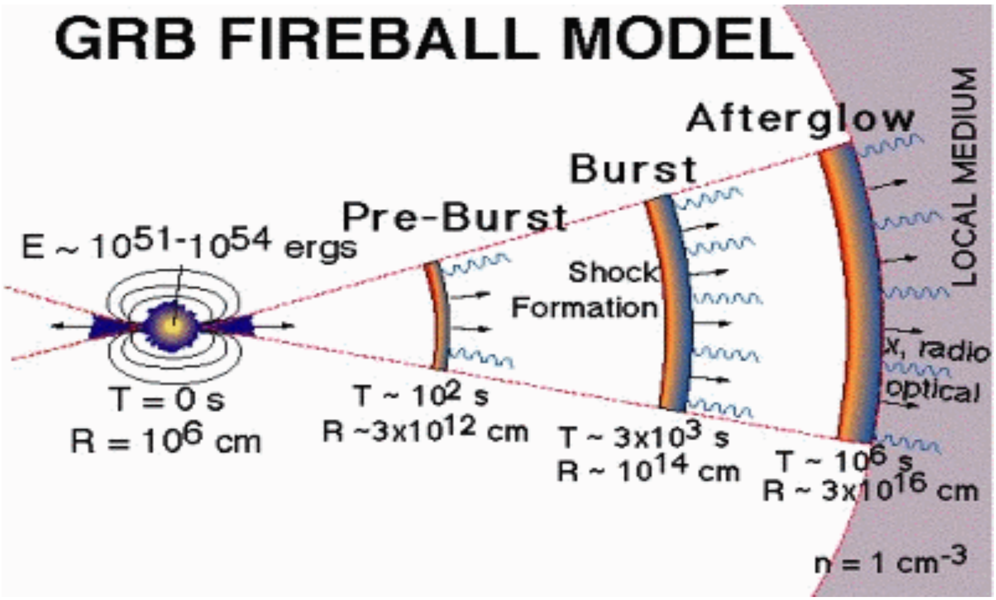


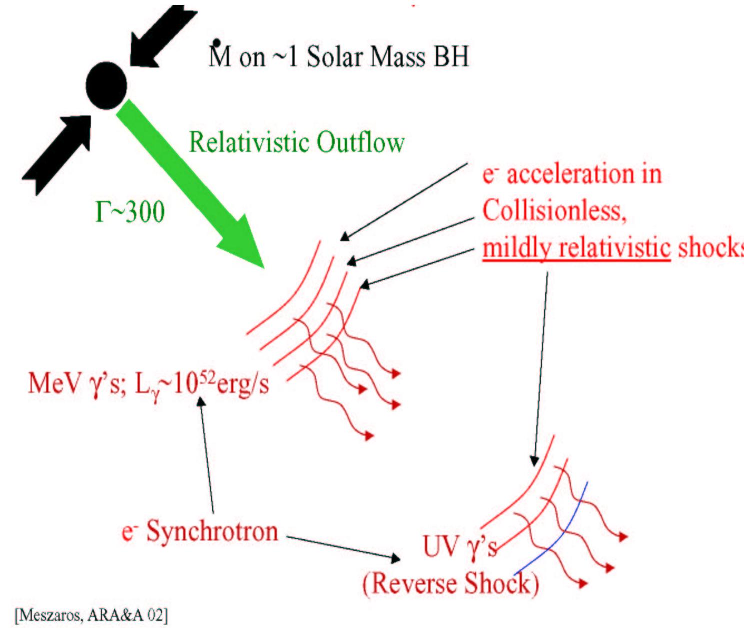
Giannios 2012

Titarchuk et al., ApJ, 2012

❑ Understanding the physical grounds of the Ep,i – Intensity correlation

➢ **Ep is a fundamental parameter in GRB prompt emission models**





➢ ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)

➢ non thermal spectra -> shocks synchrotron emission (SSM)

➢ fireball internal shocks -> prompt emission

➢ fireball external shock with ISM -> afterglow emission

Conclusions

- 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)

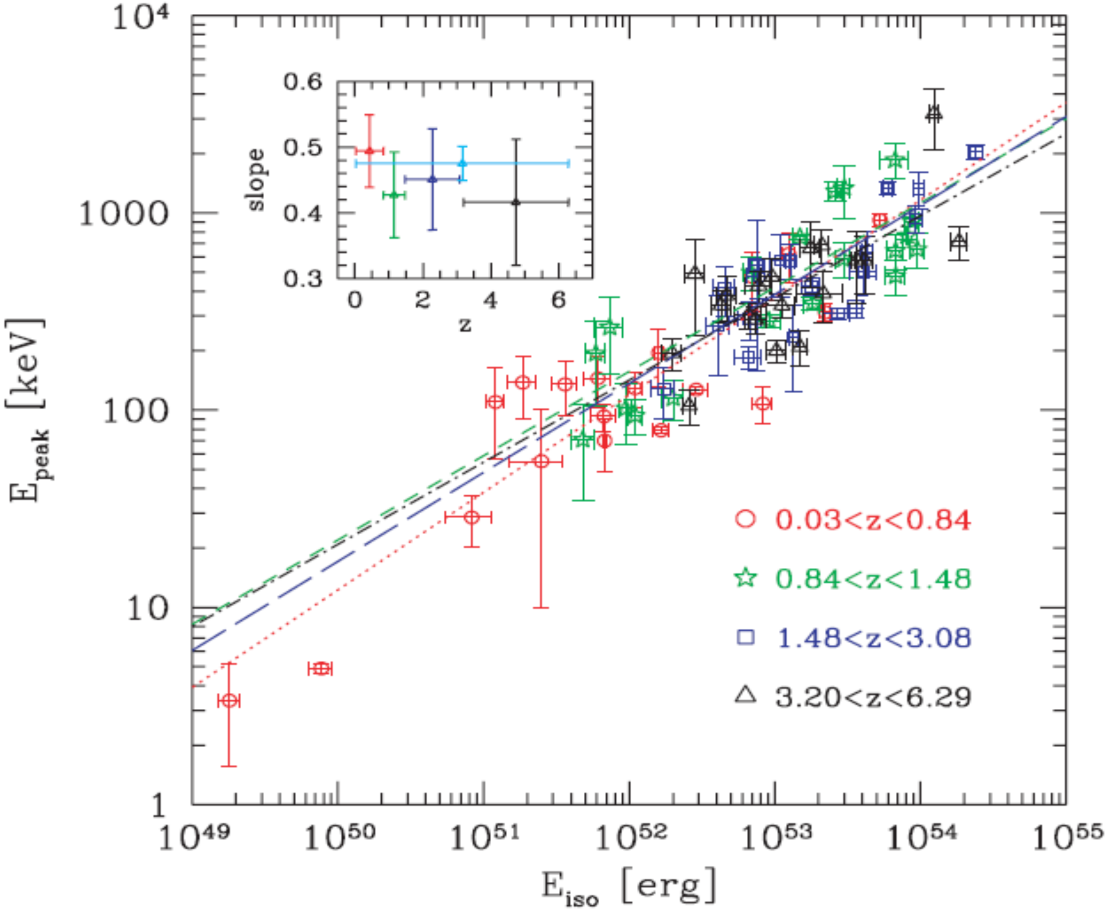
- The Ep,i – intensity correlation is one of the most robust (no firm evidence of significant selection / instrumental effects) and intriguing properties of GRBs and a promising tool for cosmological parameters

- Analysis in the last years (>2008) provide already evidence, independent on , e.g., SN Ia, that if we live in a flat ΛCDM universe, Ωm is < 1 at >99.9% c.l. (χ^2 minimizes at Ωm ~ 0.3, consistent with “standard” cosmology)

- The simulatenous 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 and investigations (physics, collimation, calibration) will allow to go beyond SN Ia (e.g.,dark energy EOS)**

❑ No evidence of evolution of index and normalization of the correlation with redshift



e.g., Ghirlanda et al. 2008

❑ Other approaches (already partly / to be) investigated

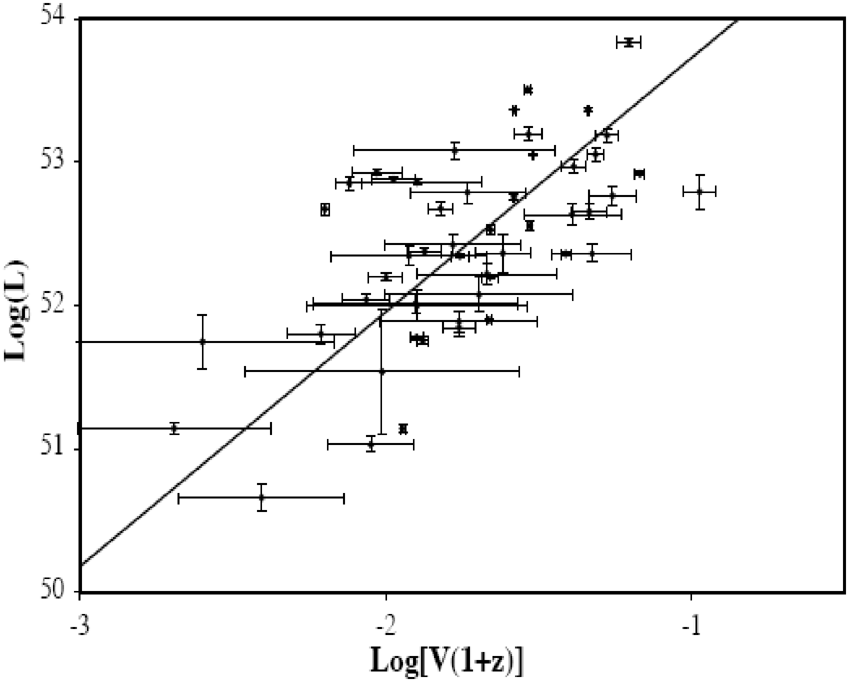
- cosmographic calibration of the Ep,i – Intensity correlation (e.g., Capozziello et al., Demianski et al.): up to now used to calibrate GRBs against SN Ia, perspectives ?

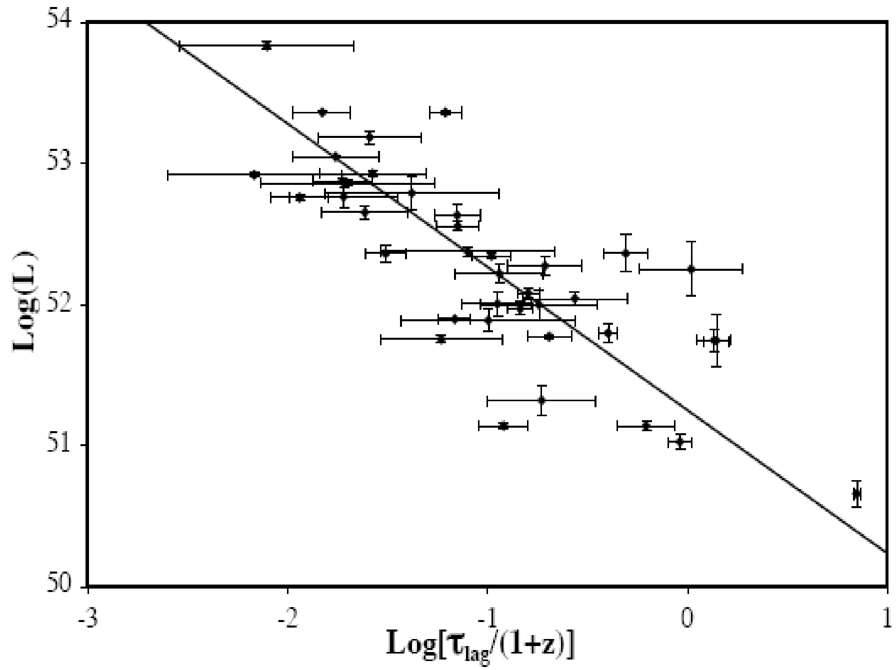
- **"self-calibration" of the correlation with a large enough number of GRBs lying within a narrow (Δz = 0.1-0.2) range of z: promising, requires sample enlargement**

- combining Ep,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 Ep-Intensity correlation by involving other prompt or afterglow properties (e.g., Dainotti et al., Margutti et al., Tsutsui et al.) -> aimed at reducing the dispersion of the correlation but risk of increasing systematics and lowering N

- using GRBs to test and constrain different cosmological models (e.g., f(r) theories)





Luminosity-Variability correlation (Reichart et al., Guidorzi et al., Rizzuto et al.)

Luminosity-time lag correlation (Norris et al.)

❑ Other approaches (already partly / to be) investigated

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

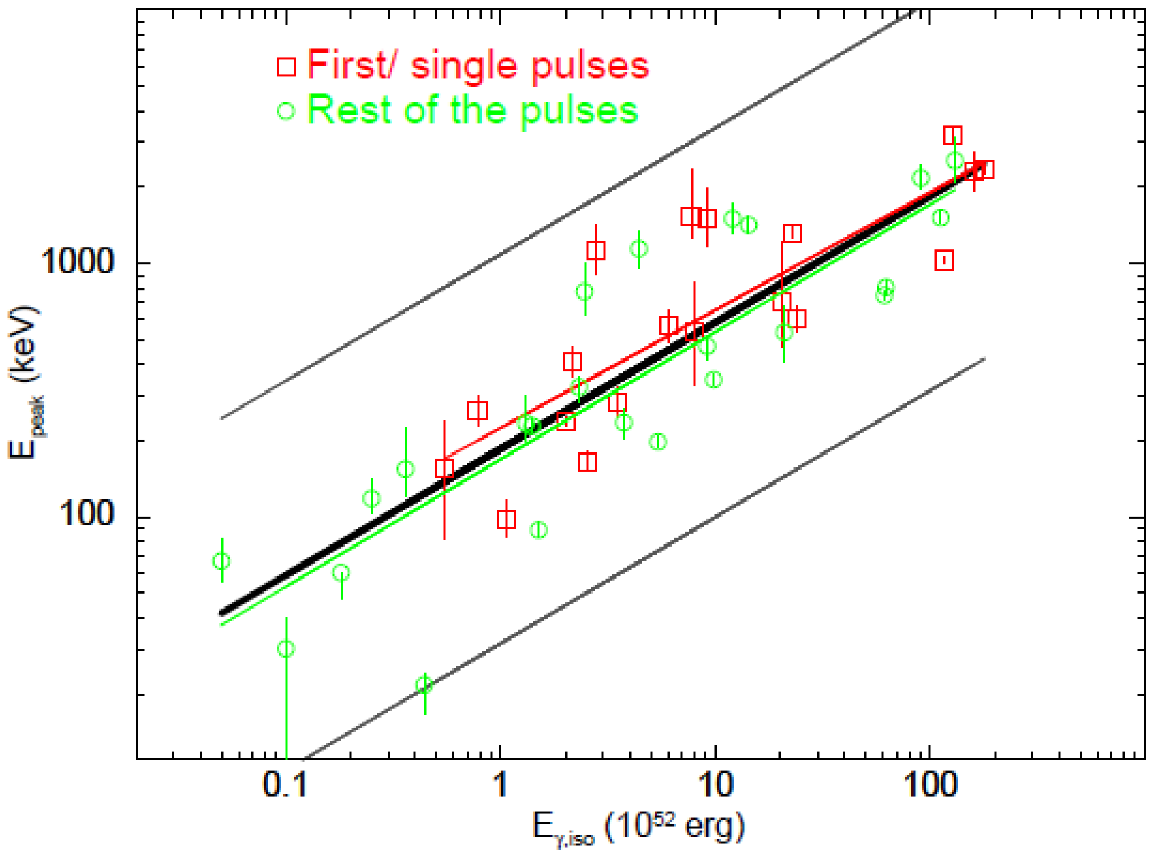
➢ **"self-calibration" of the correlation with a large enough number of GRBs lying within a narrow (Δz = 0.1-0.2) range of z): promising, requires sample enlargement**

➢ combining Ep,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 Ep-Intensity correlation by involving other prompt or afterglow properties (e.g., Dainotti et al., Margutti et al., Tsutsui et al.) -> aimed at reducing the dispersion of the correlation but risk of increasing systematics and lowering N

➢ using GRBs to test and constrain different cosmological models (e.g., f(r) theories)

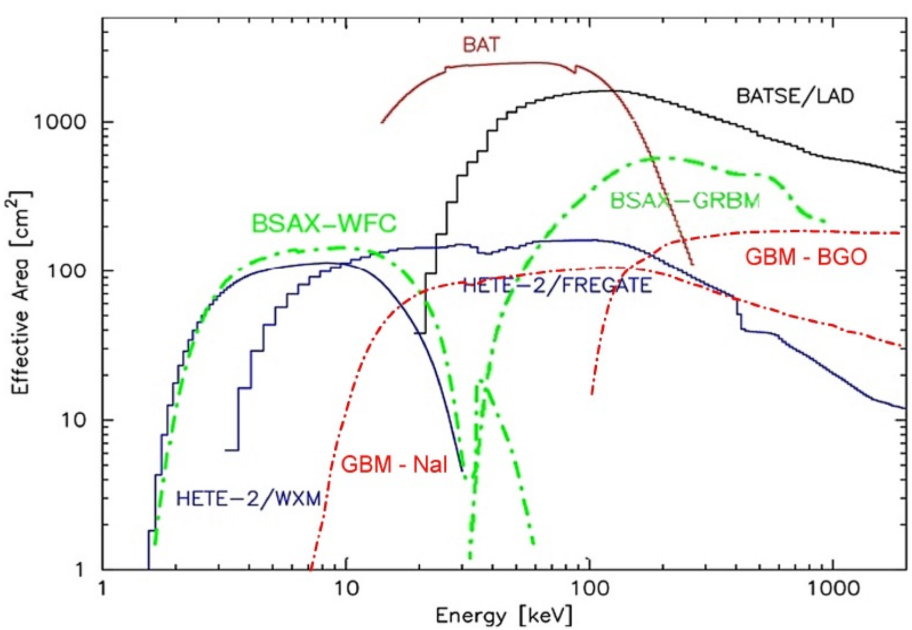
➢ Basak et al. 2013: time-resolved Ep,i – Eiso correlation



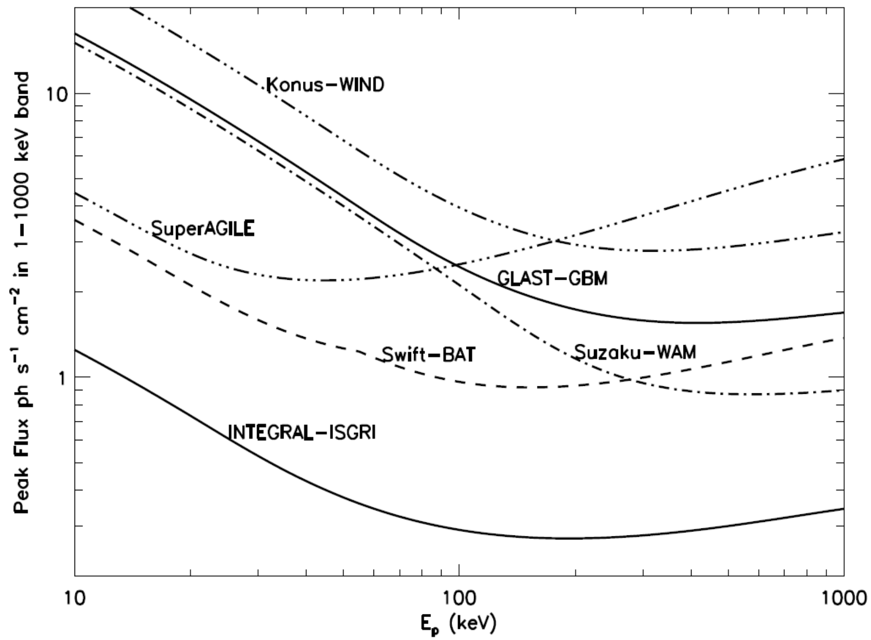
But… is the Ep,i – intensity correlation real ?

- ❑ 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 Ep,i – Eiso and other correlations



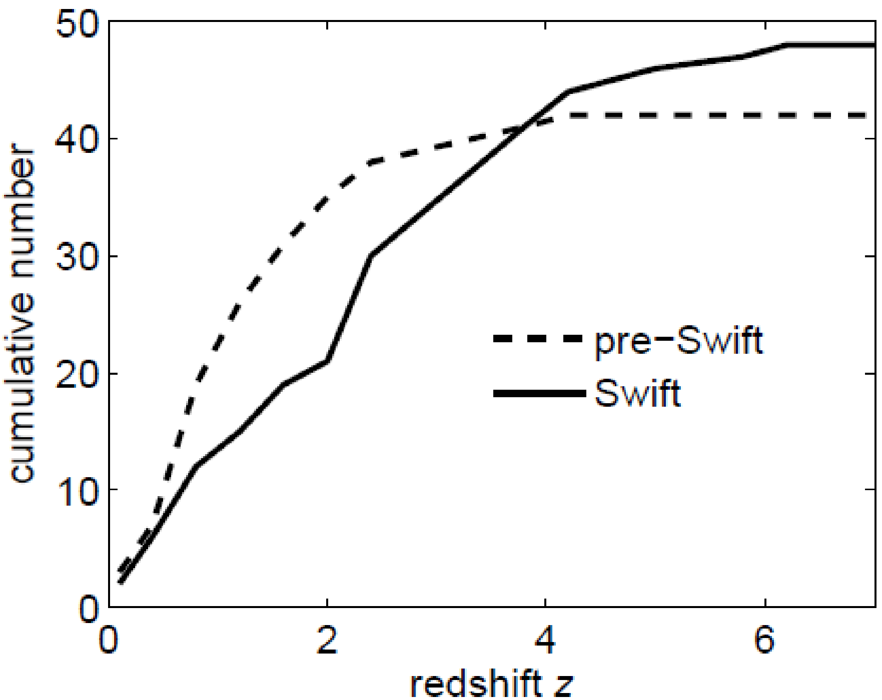
Adapted from Sakamoto et al. 2011

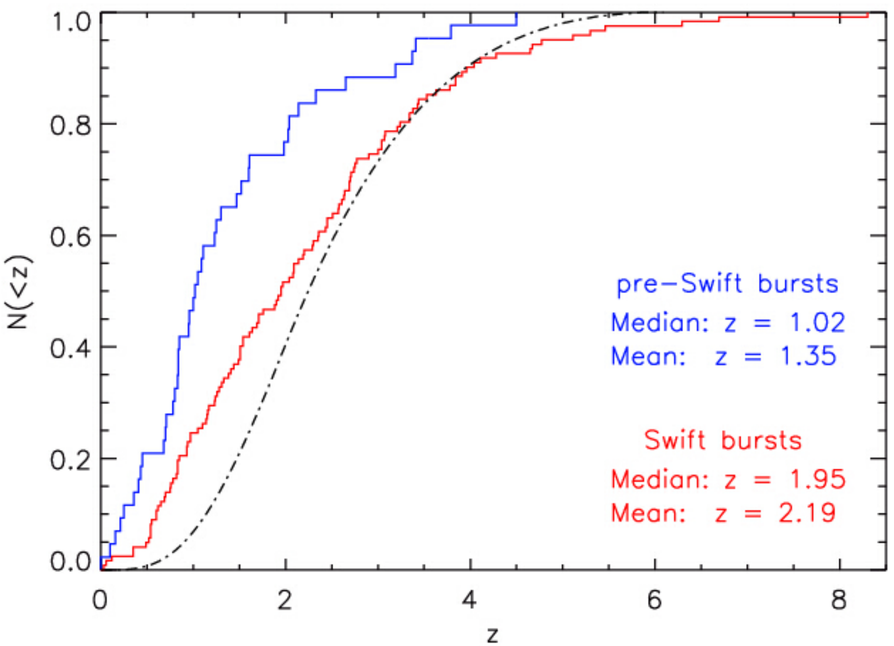


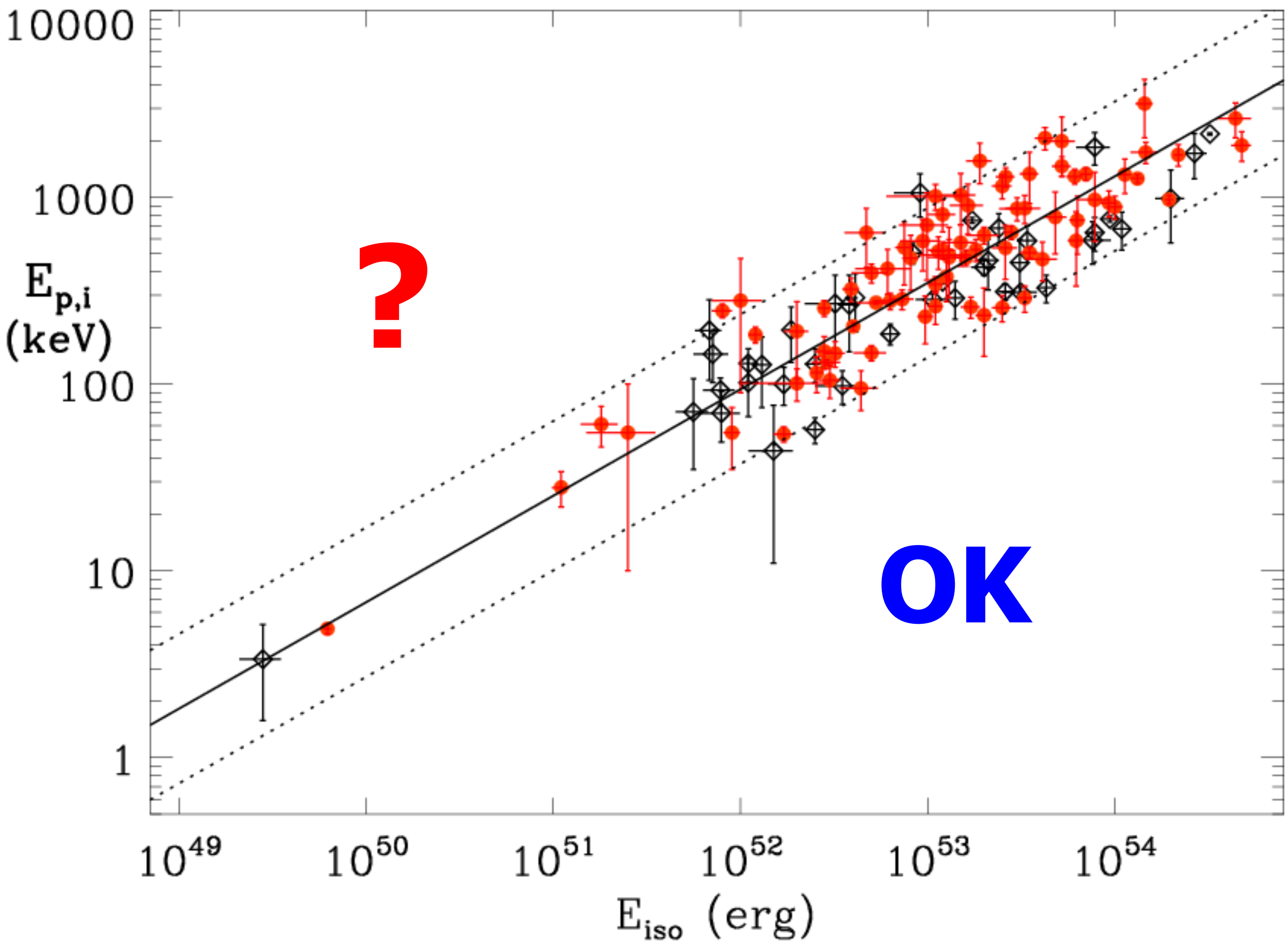
Band 2008

- 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 Ep,i – Eiso correlation





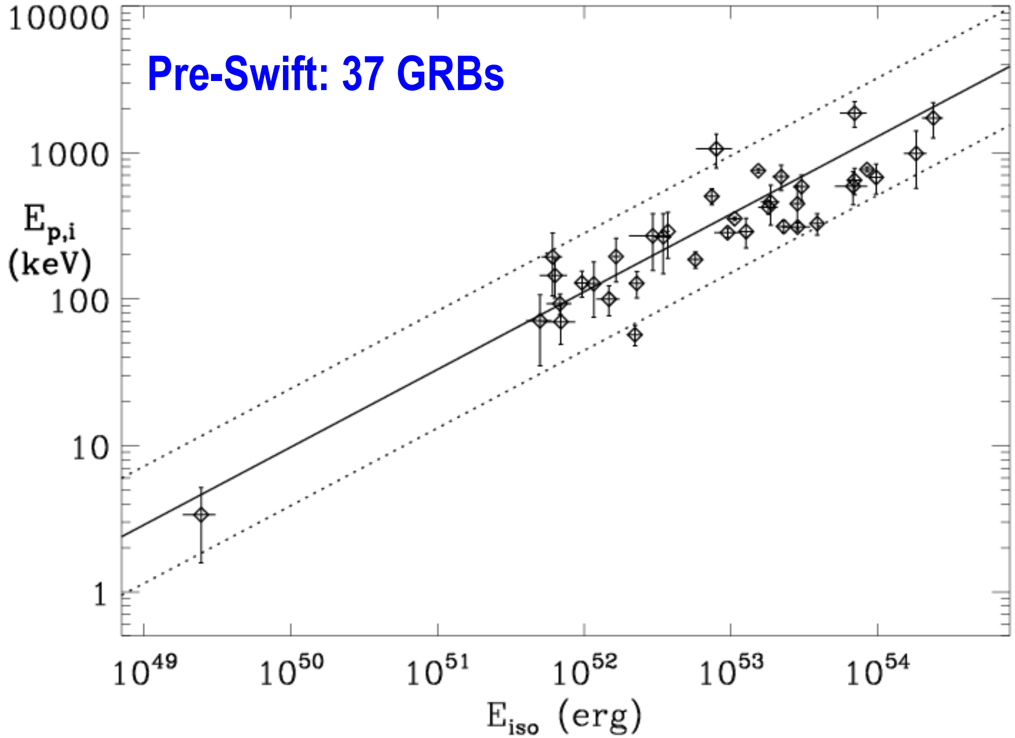


10000
1000
100
10
1
$E_{p,i}$ (keV)
?
OK
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
E_{iso} (erg)

GRBs WITH measured redshift

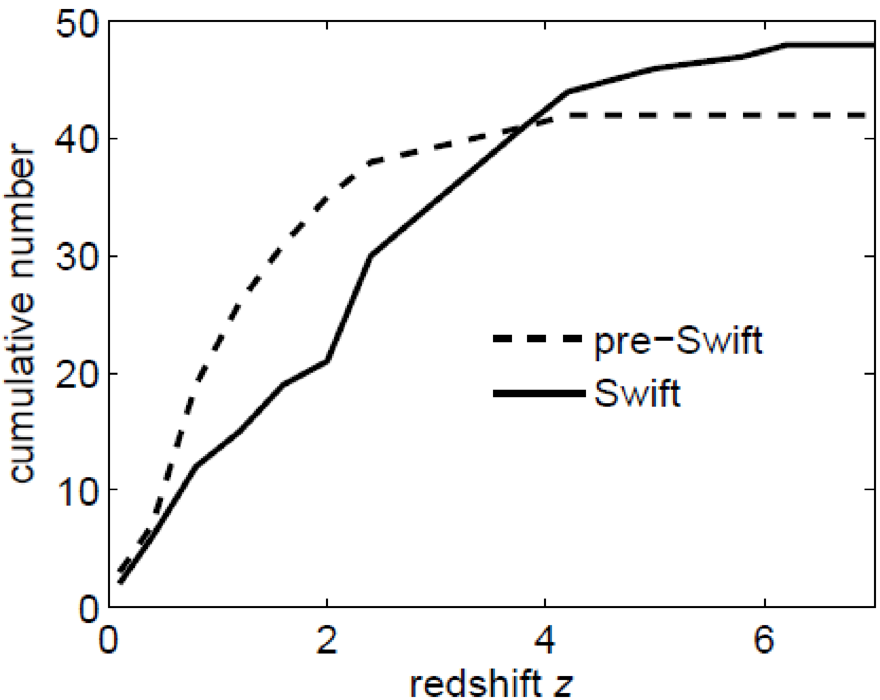
- Swift era: substantial increase of the number of GRBs with known redshift: ~45 in the pre-Swift era (1997-2003), ~230 in the Swift era (2004-2012)

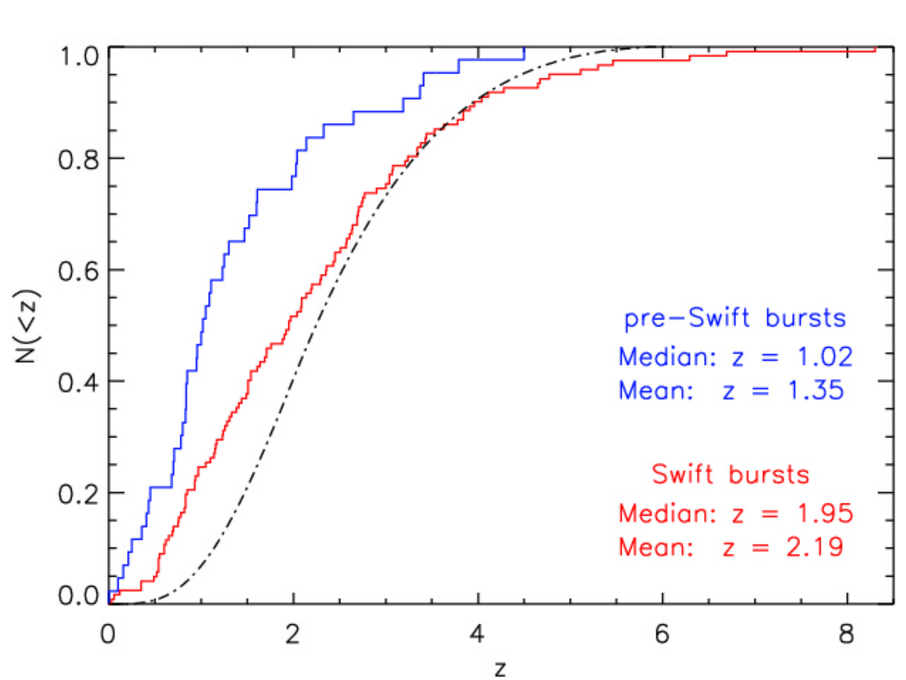
➢ thanks also to combination with other GRB experiments with broad energy band (e.g., Konus/WIND, Fermi/GBM), **substantial increase of GRBs in the Ep,i – Eiso plane**



- 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 Ep,i – Eiso correlation

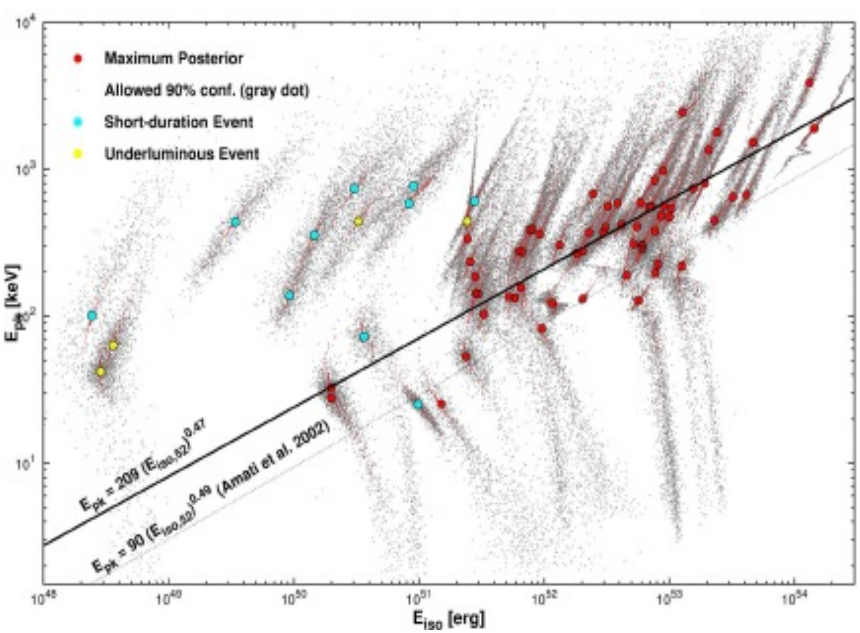


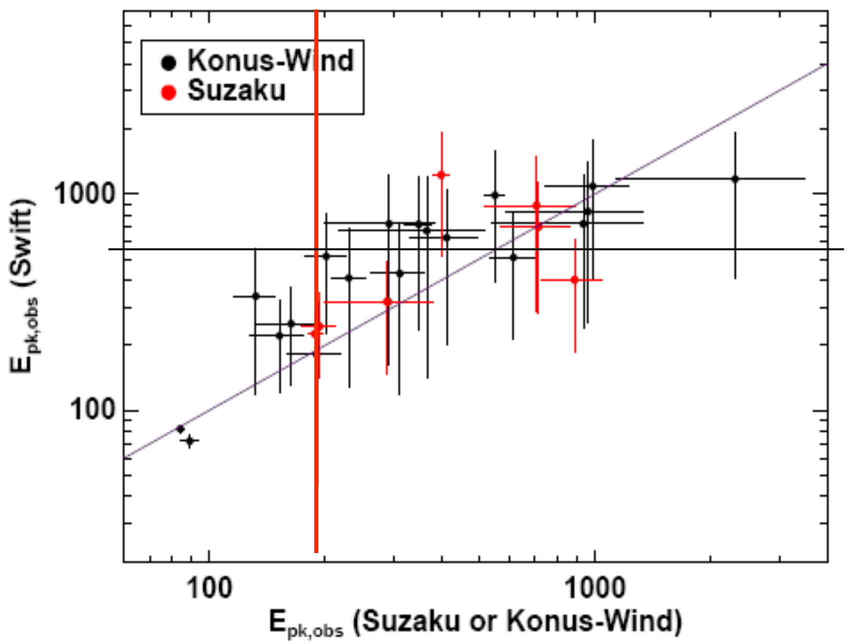


➢ Butler et al. based on analisys Swift/BAT spectra with a Bayesian method assuming BATSE Ep distribution: 50% of Swift GRB are inconsistent with the pre-Swift Ep,i - Eiso correlation

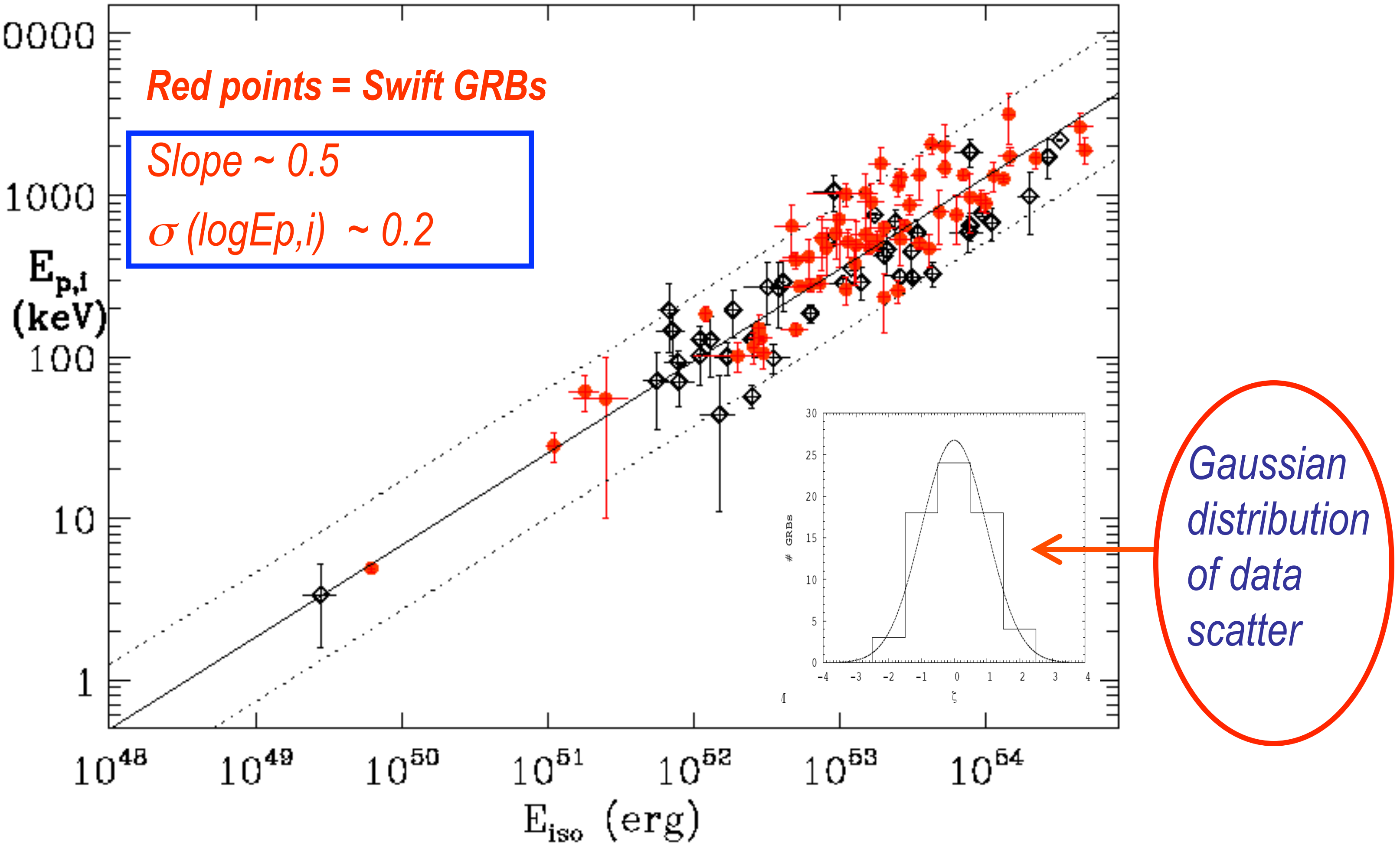
➢ BUT: comparison of Ep derived by them from BAT spectra using a Bayesian method and those MEASURED by Konus/Wind show that **BAT cannot measure Ep > 200 keV (as expected, given its 15-150 keV passband)**

➢ 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**



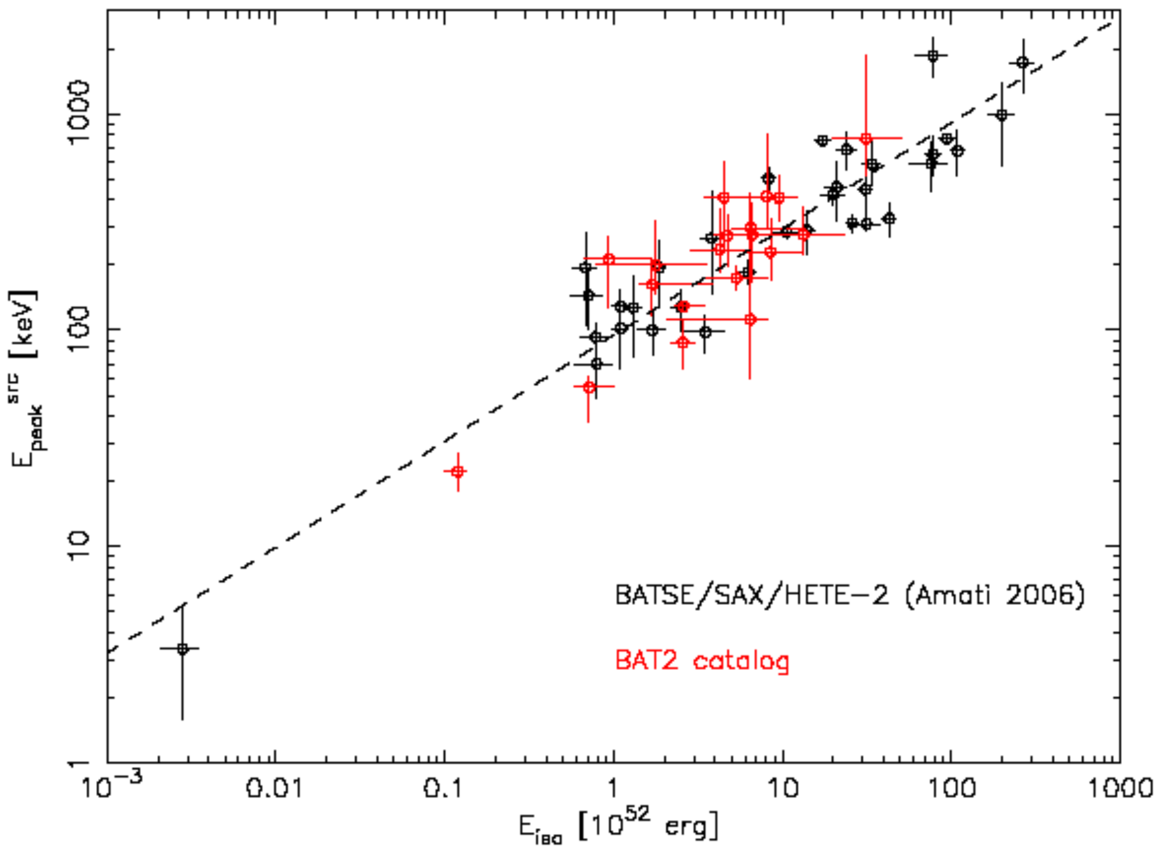
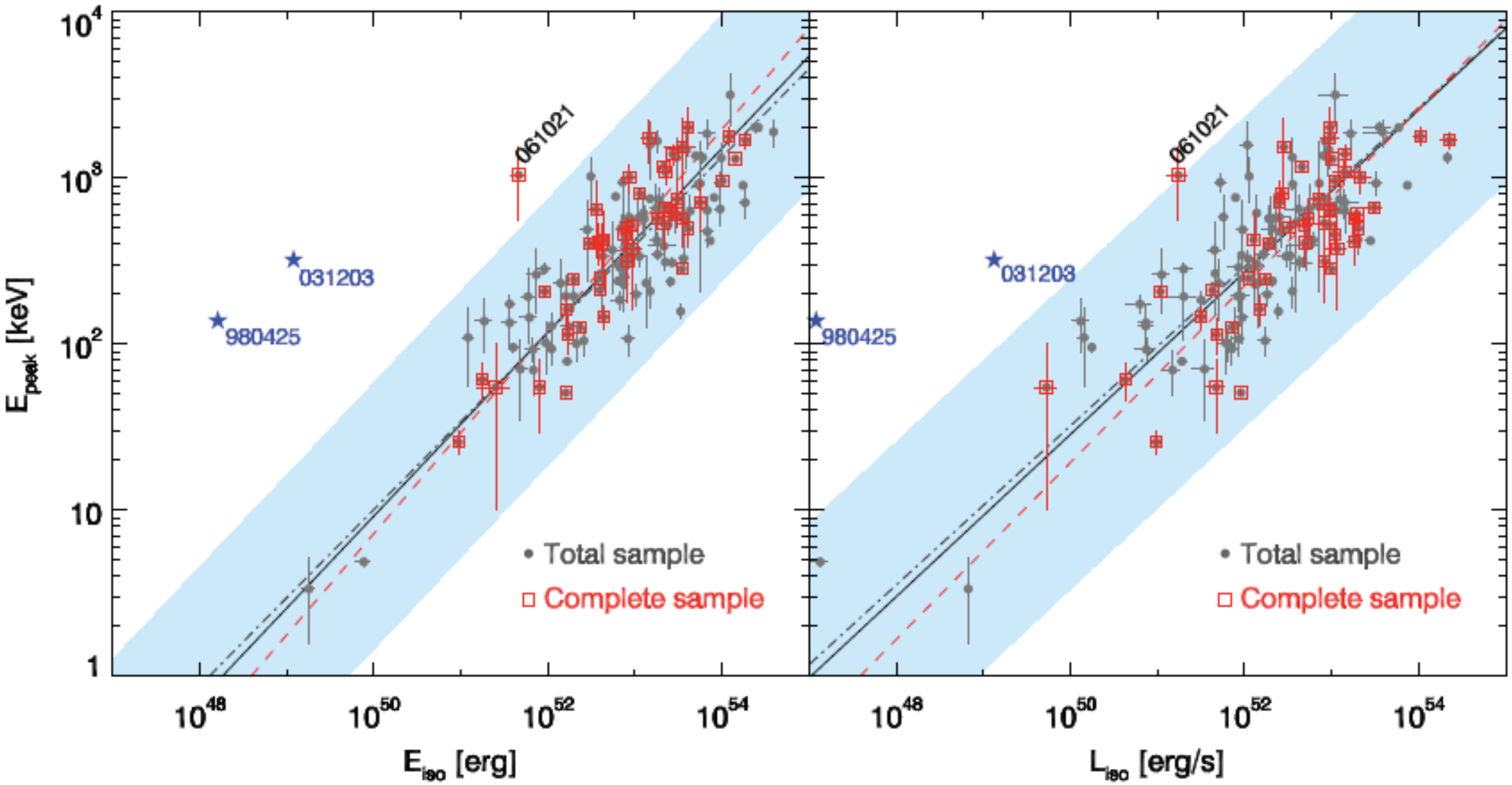


Fig. 33.— The correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ for the *Swift* GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ reported by Amati (2006): $E_{\rm peak}^{\rm src} = 95 \times (E_{\rm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

Sakamoto et al. 2011

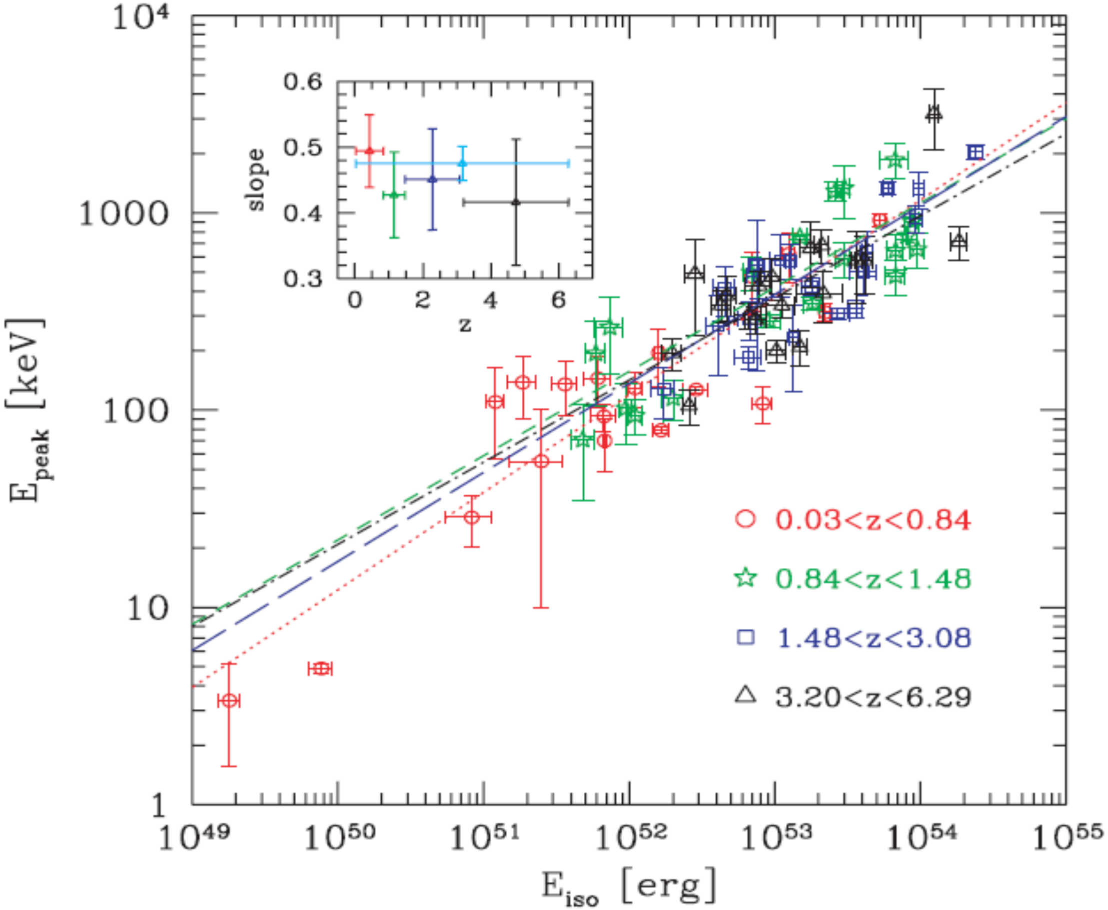
❑ Nava et al. 2012: Ep,i – Eiso and Ep – Lp,iso correlations confirmed by the analysis of the complete sample by Salvaterra et al. 2011 -> further evidence of low impact of selection effects in redshift

❑ GRB 061021 possible outlier, but 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



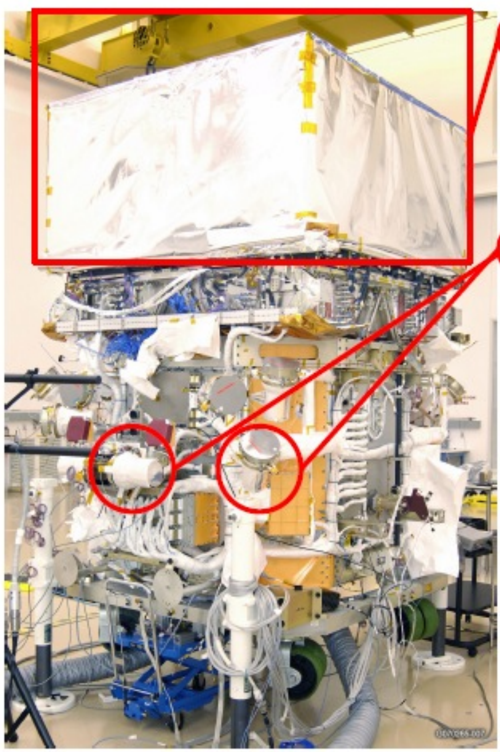
Nava et al. 2012, "complete sample of Salvaterra et al. 2011"

❑ No evidence of evolution of index and normalization of the correlation with redshift

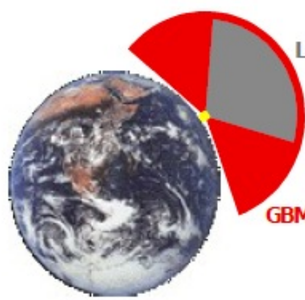


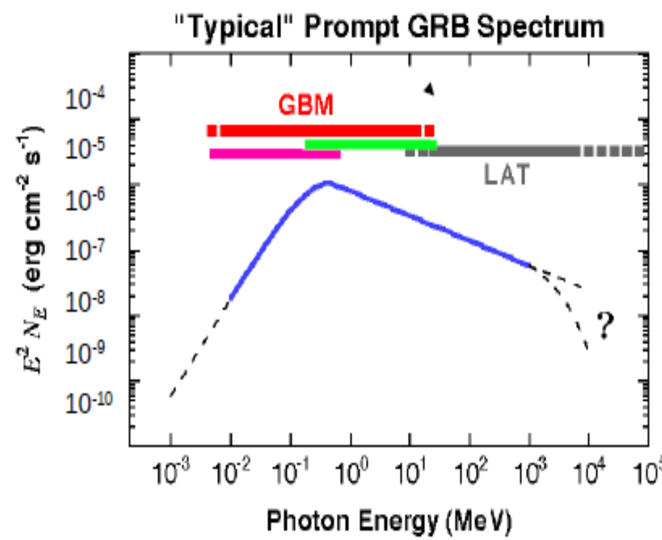
Ghirlanda et al. 2008

- 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**



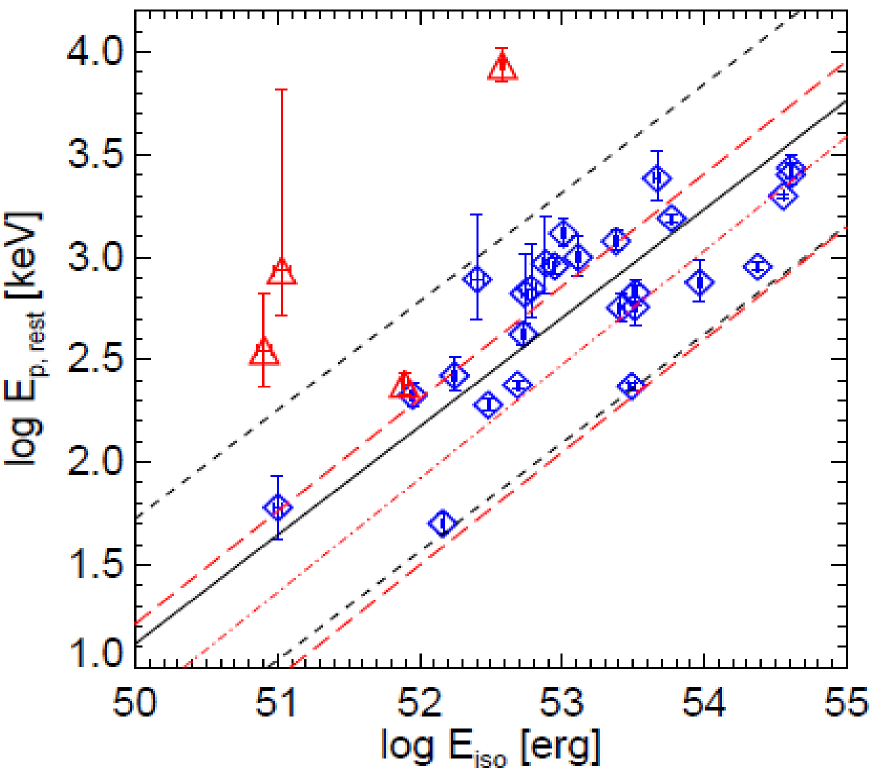
- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.

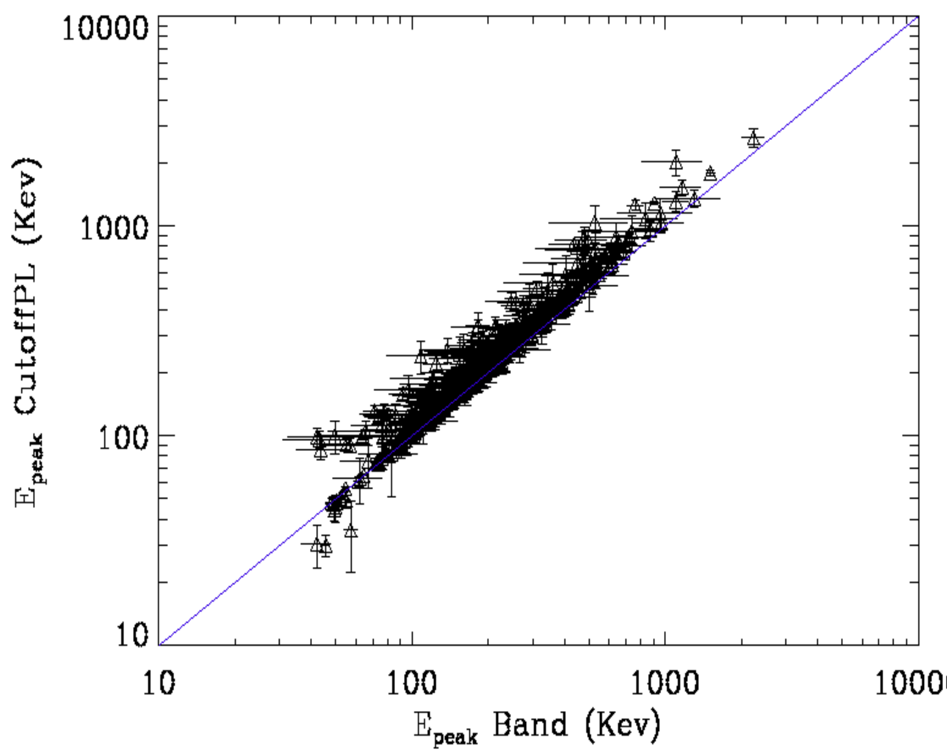




- *Gruber et al (2011, official Fermi team)*: *all Fermi/*GBM long GRBs with known z are consistent with Ep,i – Eiso correlation, short GRBs are not

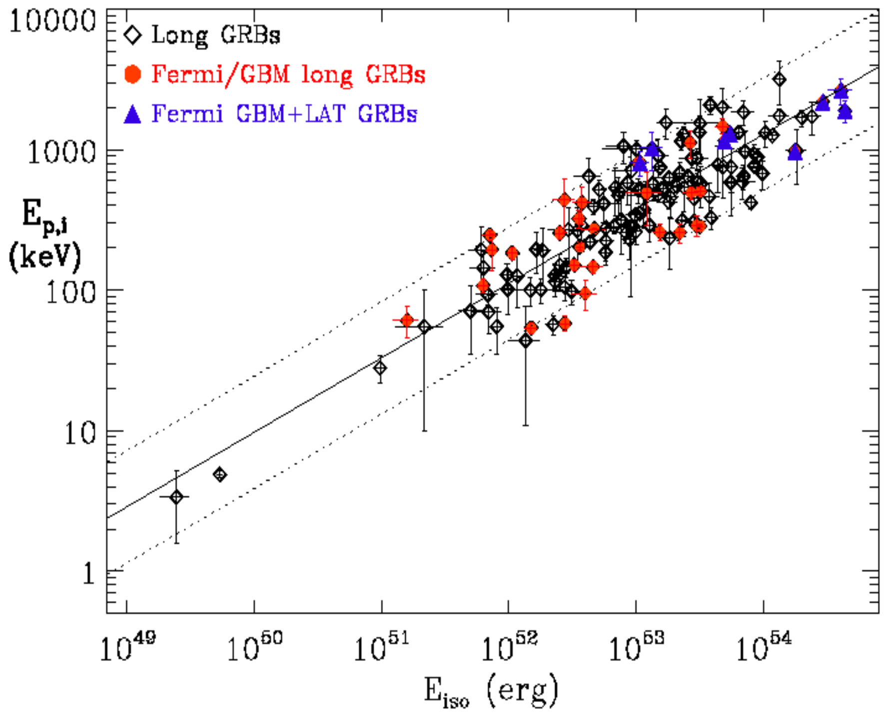
- slight overestimate of normalization and dispersion possibly due to the **use, for some GRBs, of the CPL model instead of the Band model (-> overestimate of Ep, underestimate of Eiso)**



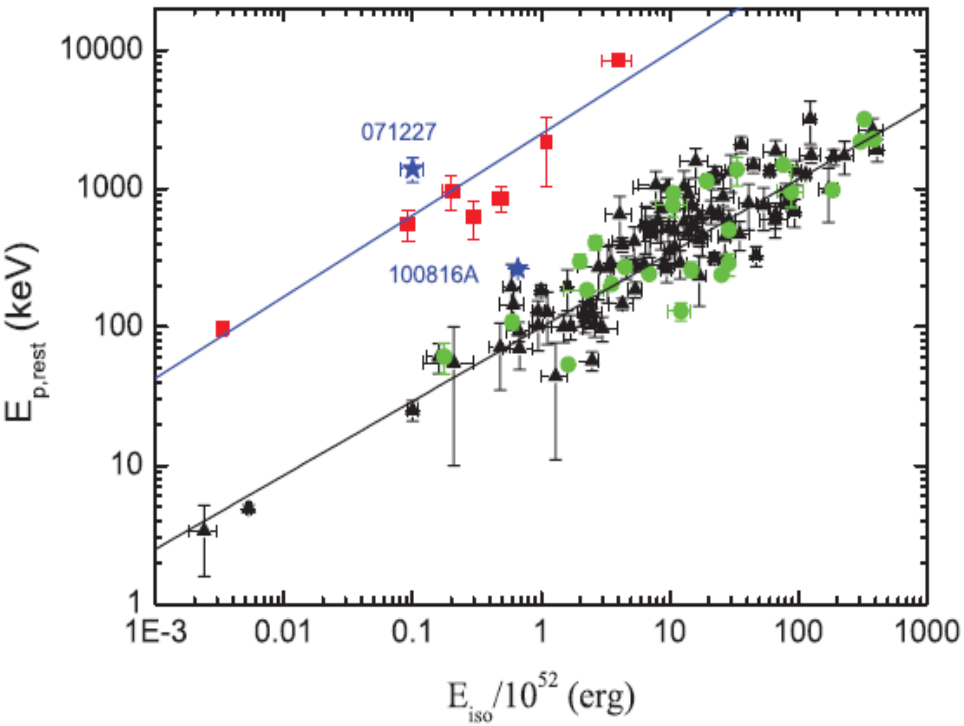


Gruber et al. 2011

❑ 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)

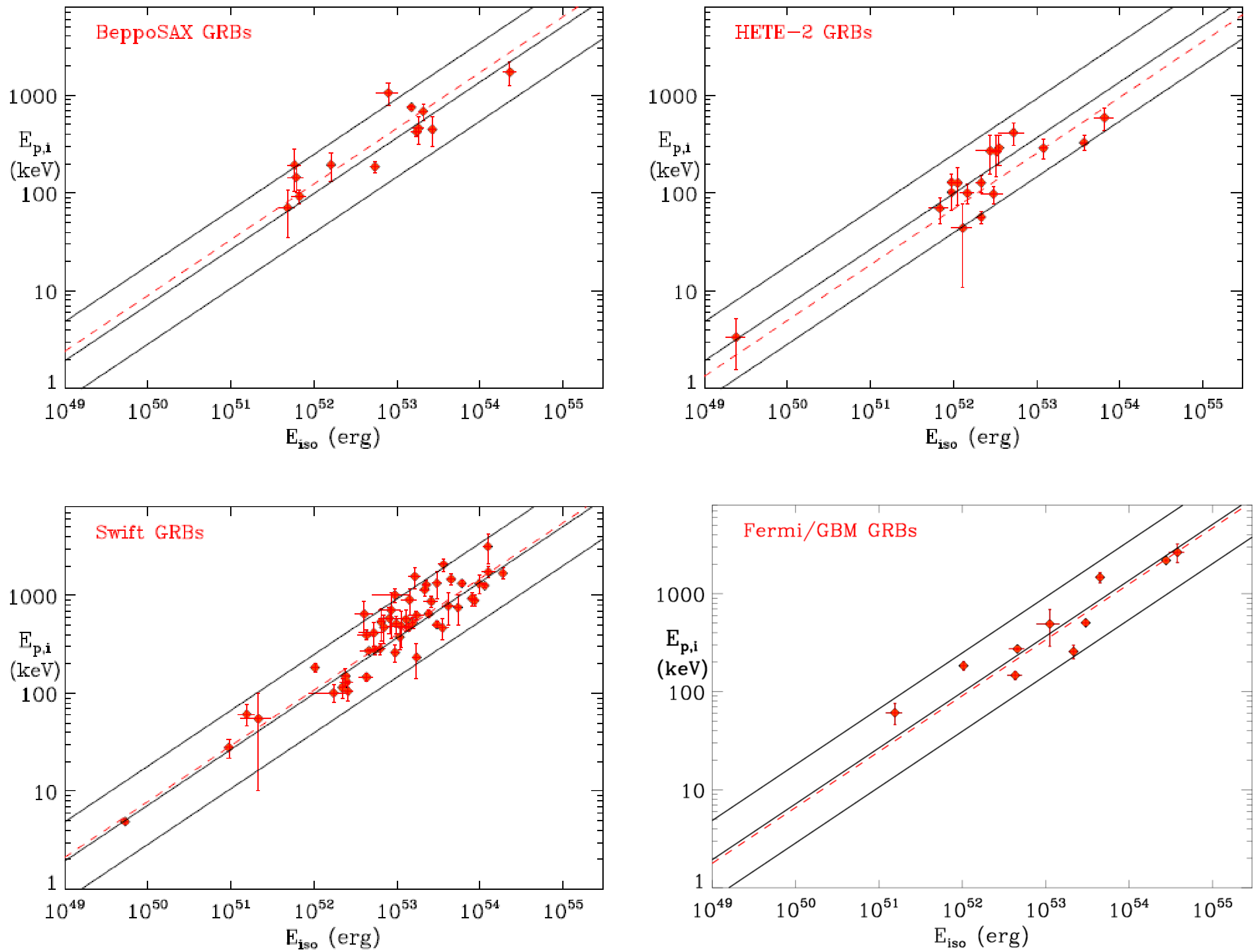


Amati 2012

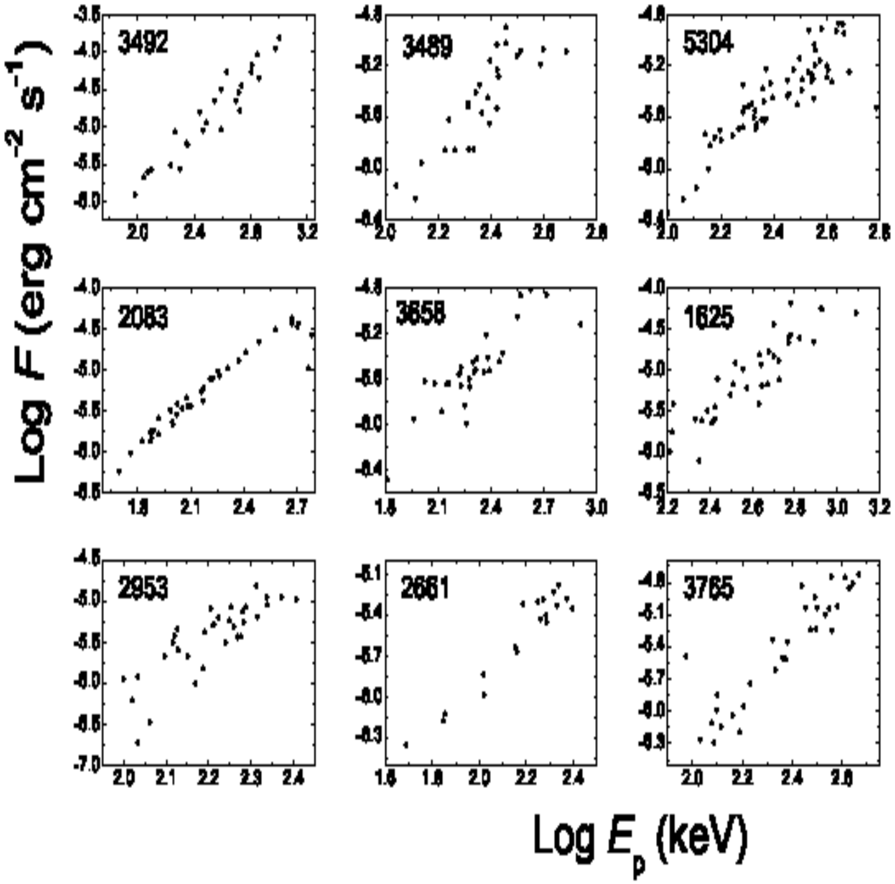


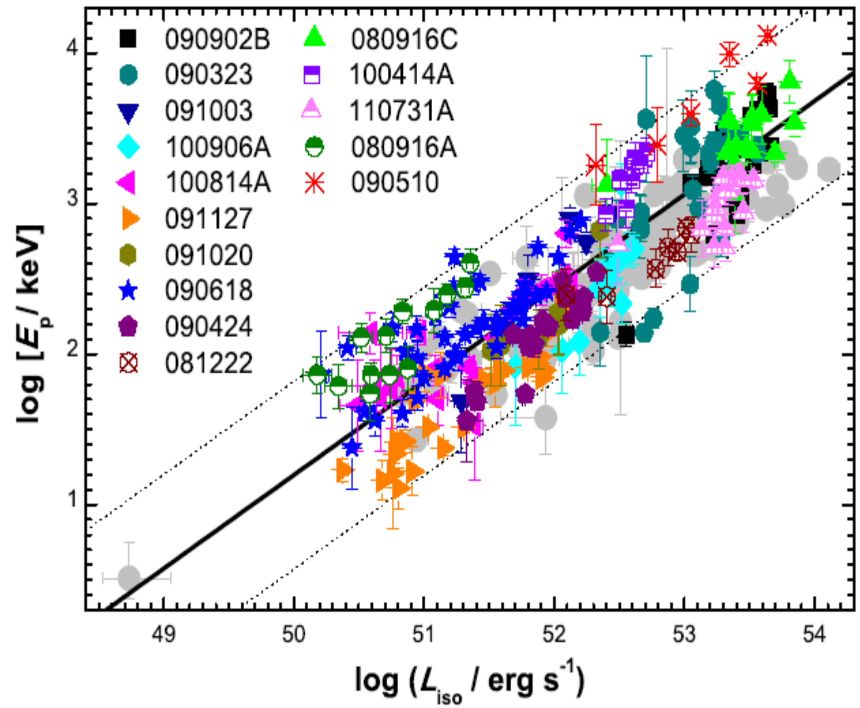
Zhang et al. 2012

❑ 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 Ep,i– Liso 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**

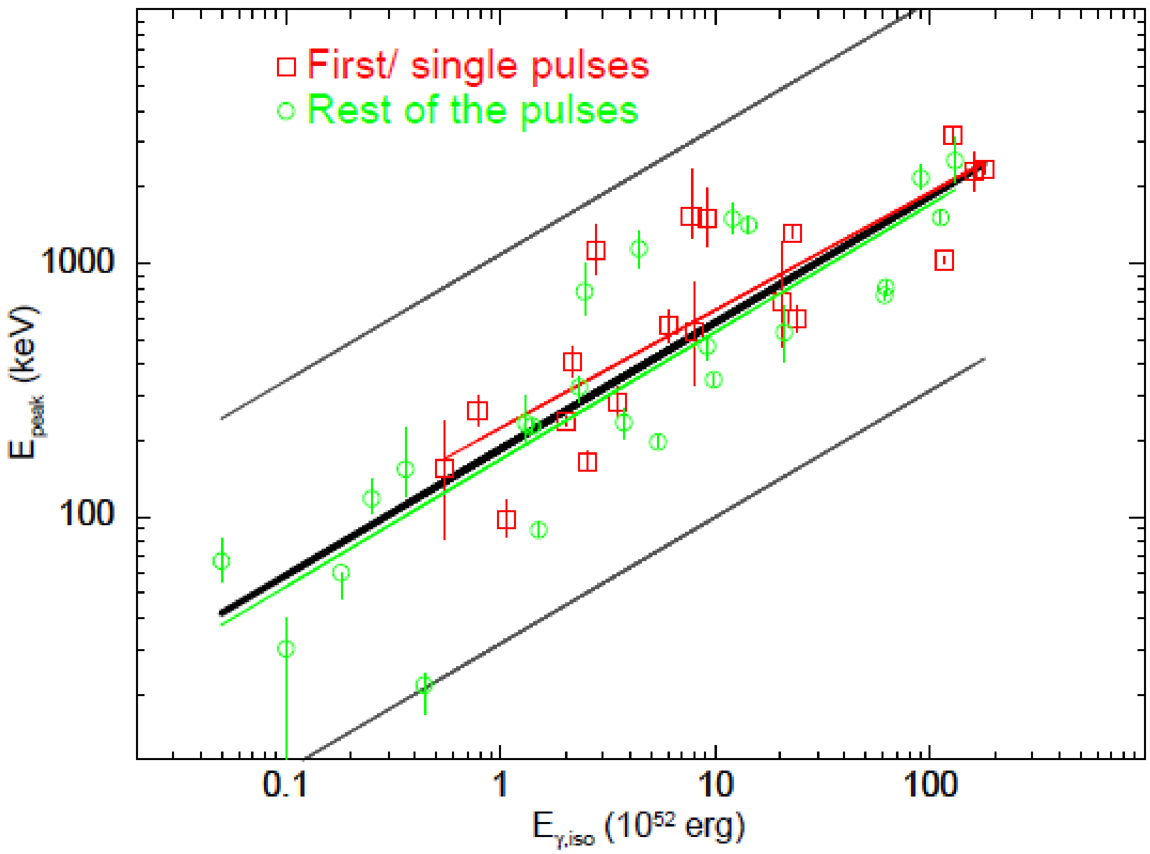




BATSE (Liang et al., ApJ, 2004)

Fermi (e.g., Li et al. , ApJ, 2012)

➢ Basak et al. 2013: time-resolved Ep,i – Eiso 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**

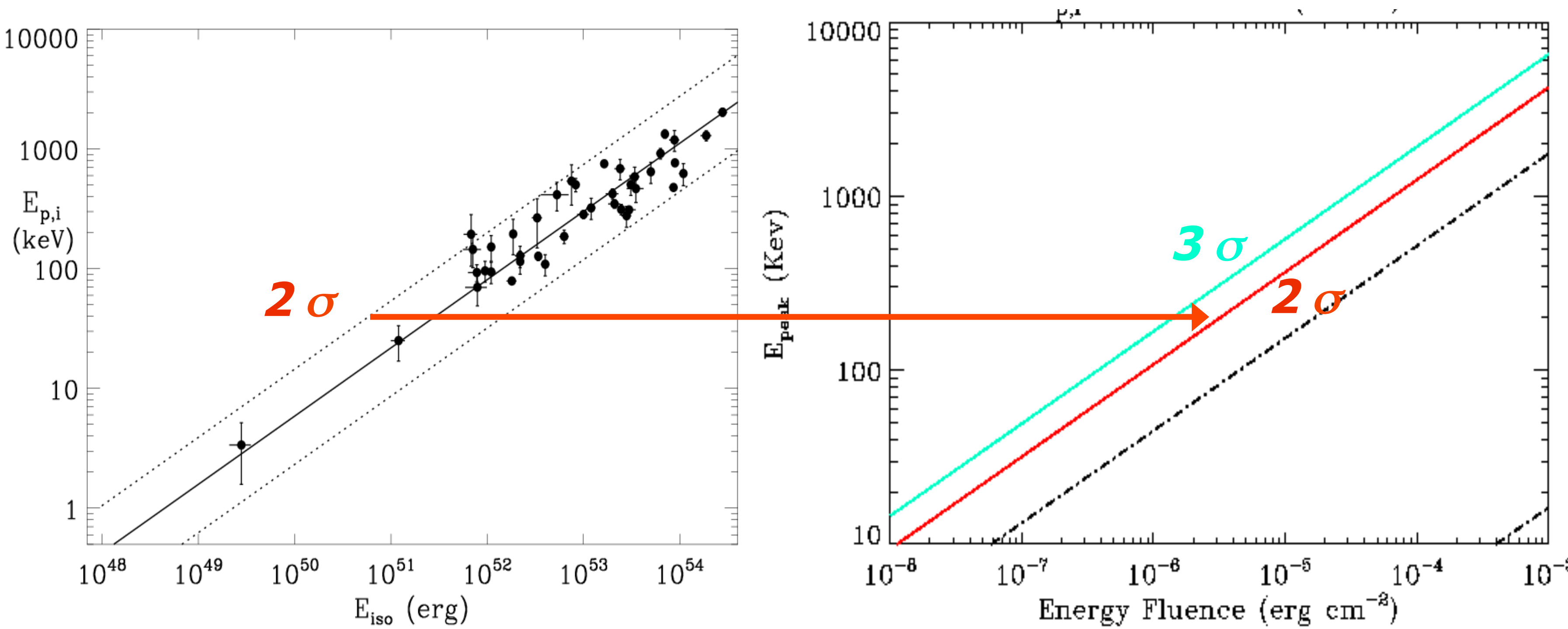
- in addition: Ghirlanda et al. (2005), Bosnjak et al. (2005), Nava et al. (2008), Ghirlanda et al. (2009) showed that **most** BATSE GRBs with unknown redshift **are potentially consistent** with the **correlation**

- 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 Ep,i – Eiso correlation into an Ep,obs – Fluence correlation

Intrinsic (cosm. Rest-frame) plane

Observer’s plane



GRBs WITH redshift (130)

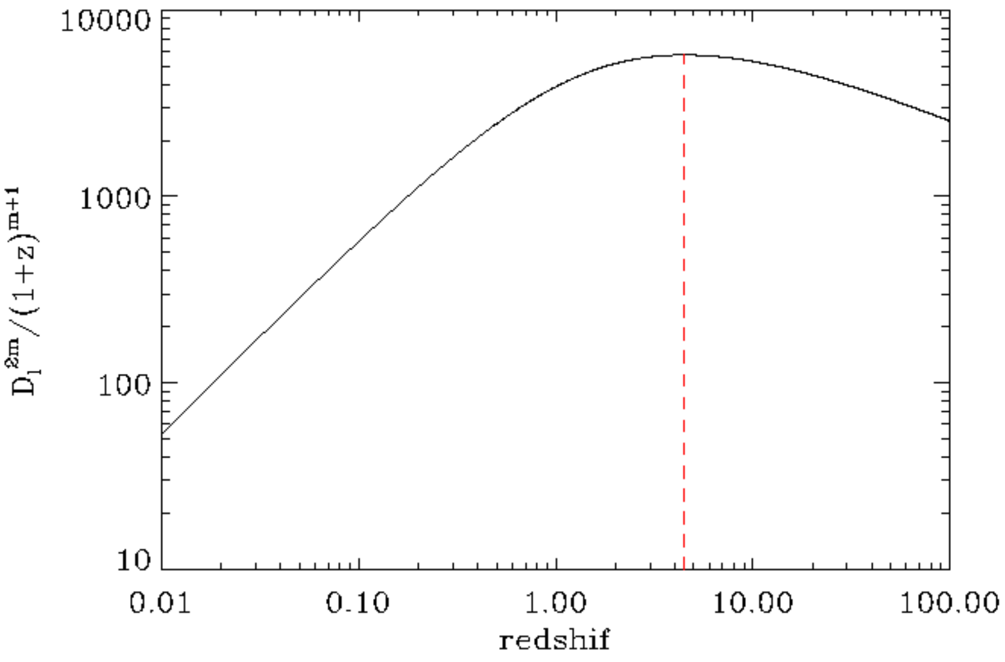
GRBs WITHOUT redshift (thousands)

- method: unknown redshift -> **convert the Ep,i – Eiso correlation into an Ep,obs – Fluence correlation**

$$E_{\rm peak}^{\rm obs}(1+z) = k\left(\frac{4\pi d_{\rm L}^2 F}{1+z}\right)^a \rightarrow E_{\rm peak}^{\rm obs} = kF^a f(z); \qquad f(z) = \frac{(4\pi d_{\rm L}^2)^a}{(1+z)^{1+a}}$$

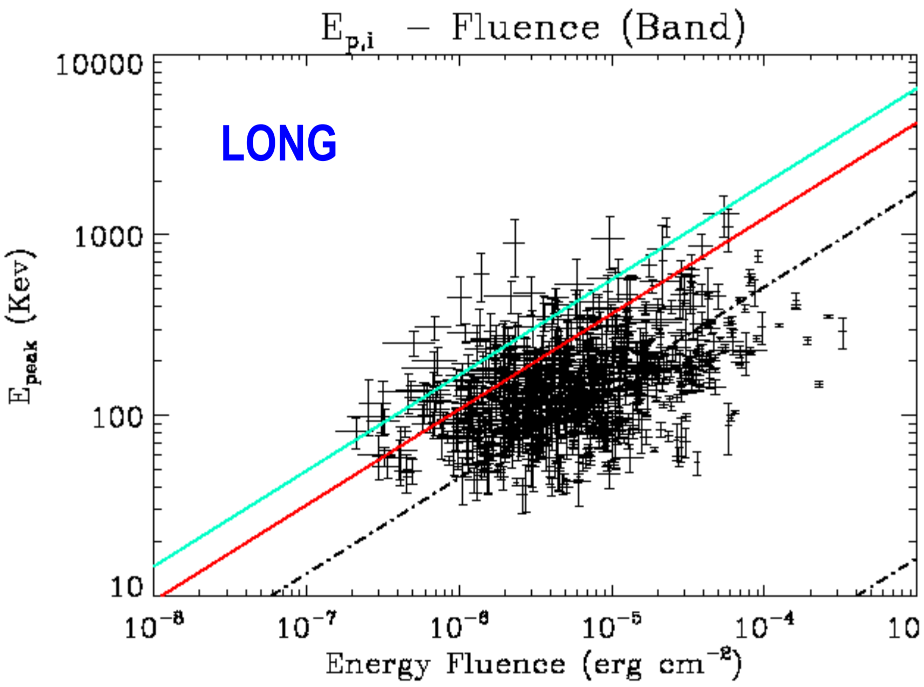
- the fit of the updated Ep,i – Eiso GRB sample with the maximum –likelihood method accounting for extrinsic variance provides a=0.53, k= 102, σ = 0.19

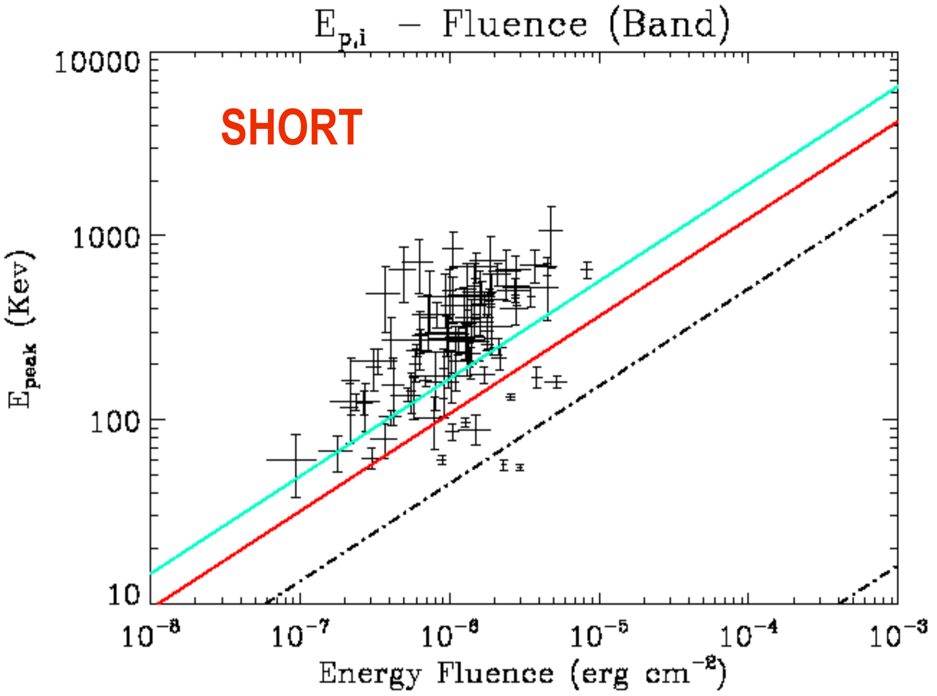
- for these values f(z) maximizes for z between 3 and 5



❑ Amati, Dichiara et al. (2013, in prep.): consider fluences and spectra from the Goldstein et al. (2010) BATSE complete spectral catalog (on line data)

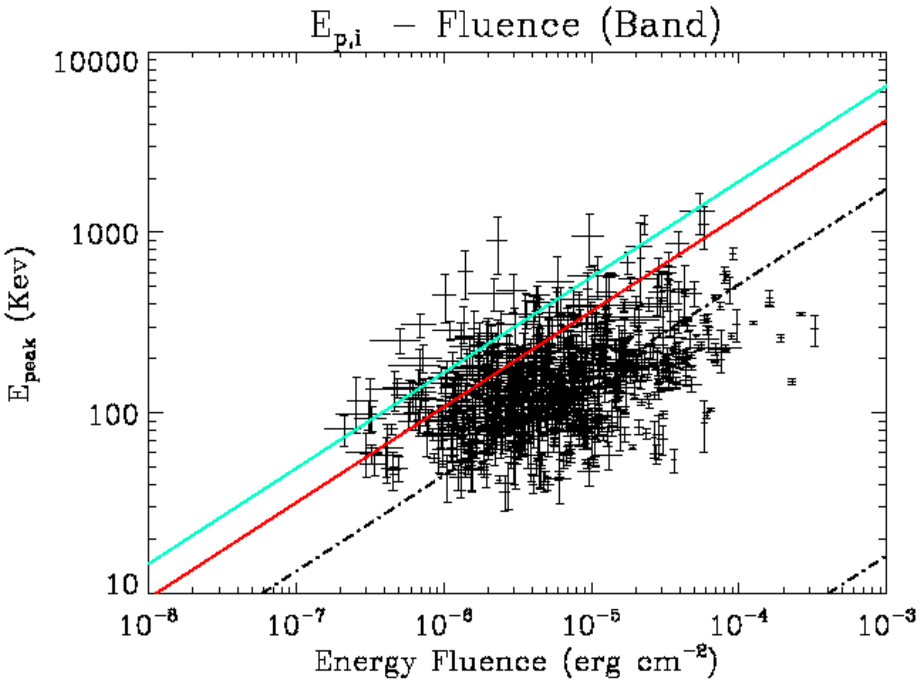
❑ considered long (777) and short (89) GRBs with fit with the Band-law and uncertainties on Ep and fluence < 40%



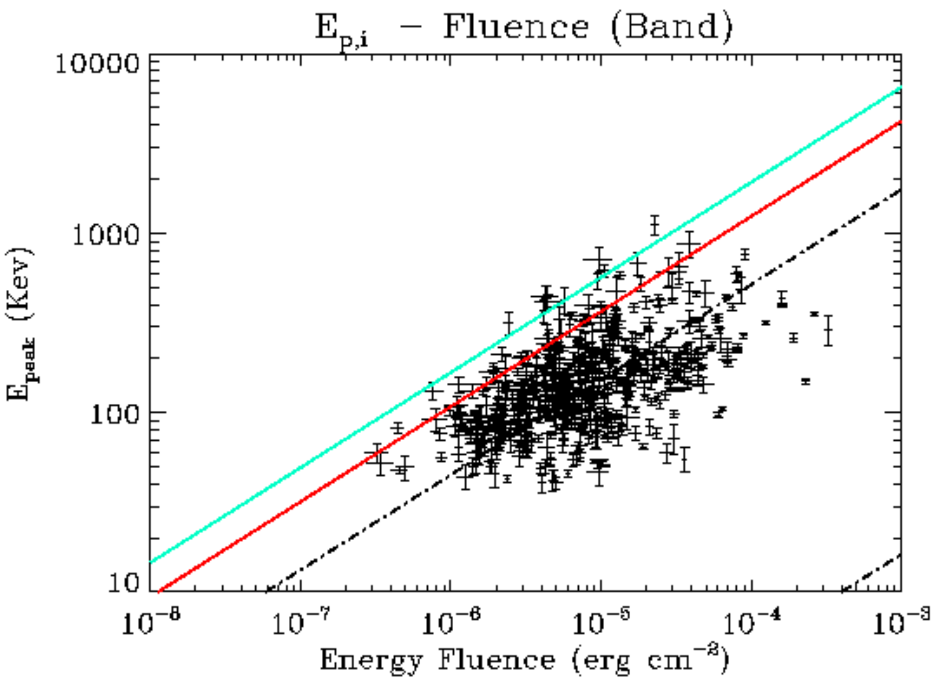


➢ **most long GRBs are potentially consistent with the Ep.i – Eiso correlation, most short GRBs are not**

❑ ALL long GRBs with 20% uncertainty on Ep and fluence (525) are potentially consistent with the correlation

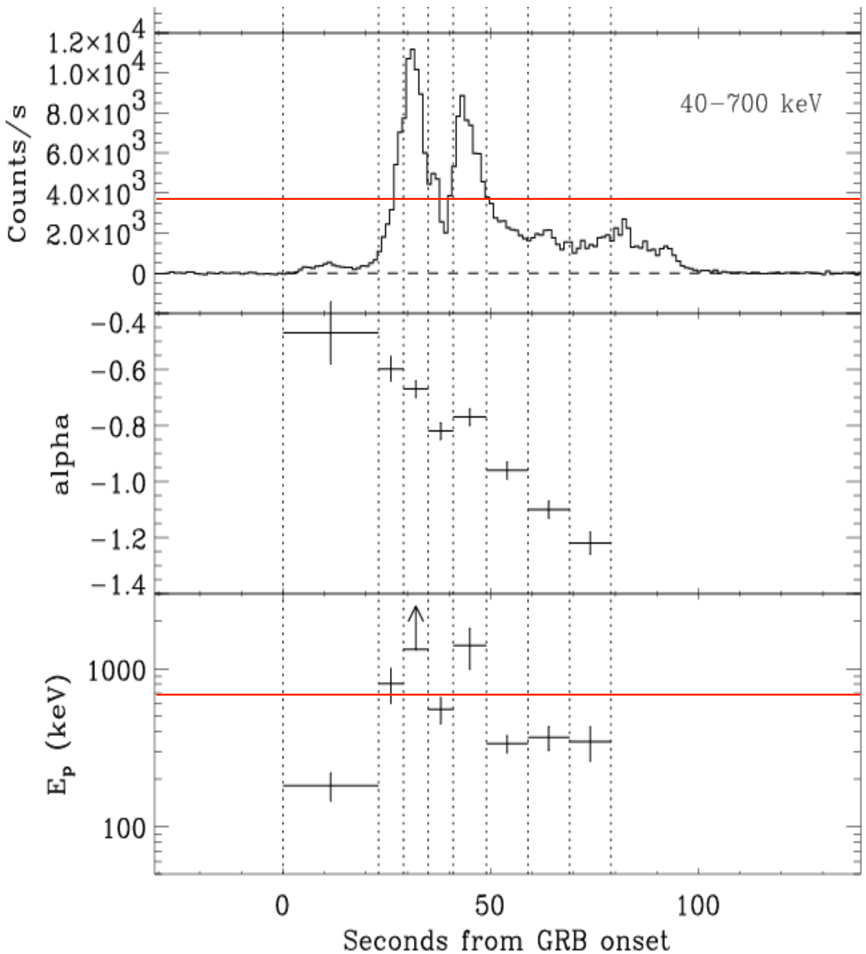


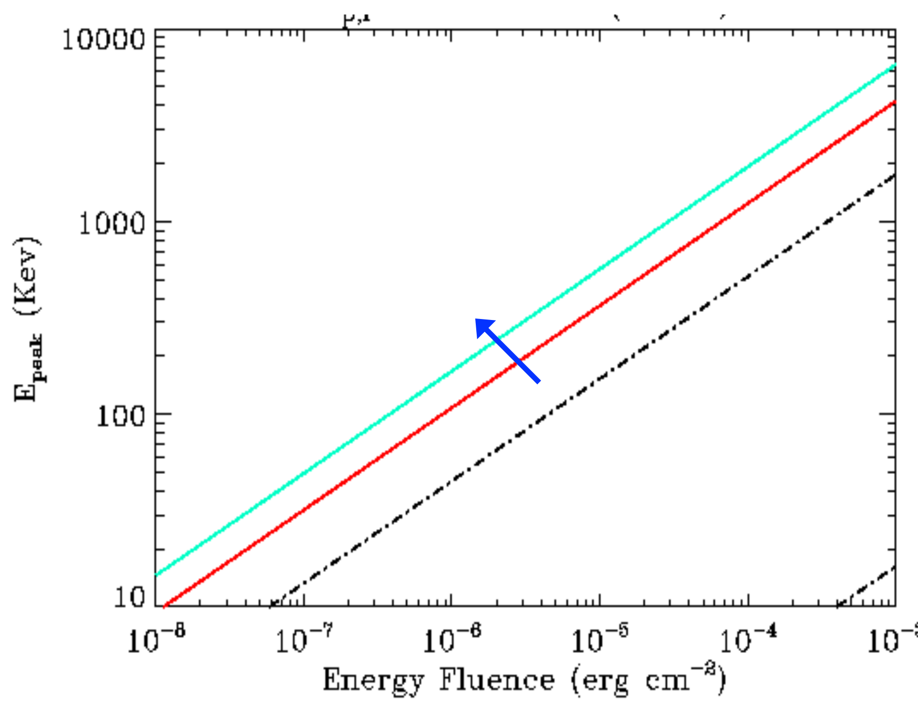
LONG, 40% unc.



LONG, 20% unc.

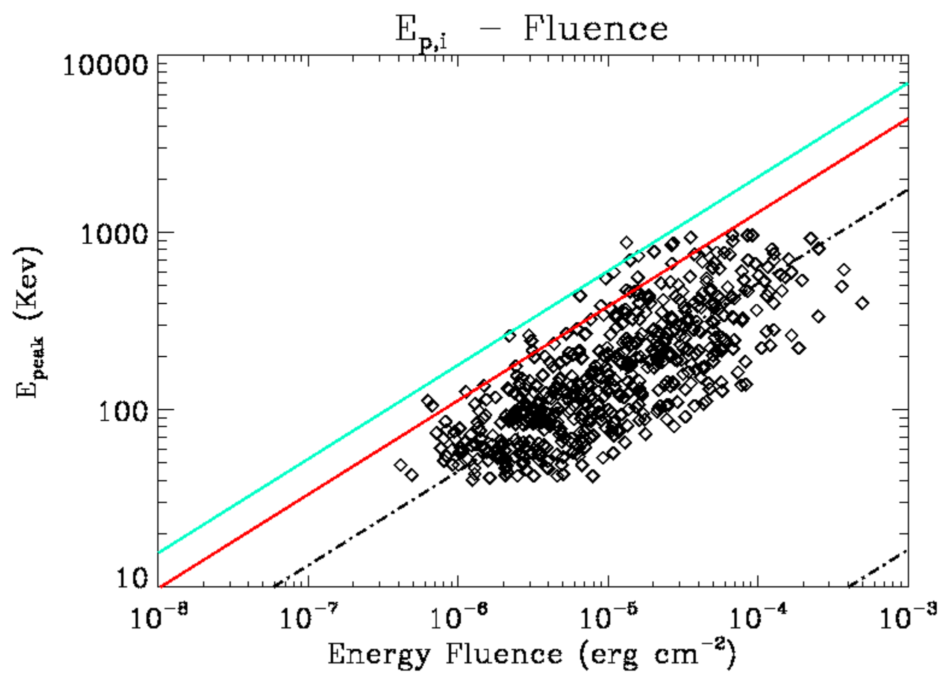
- measure only the harder portion of the event: overestimate of Ep and underestimate of the fluence

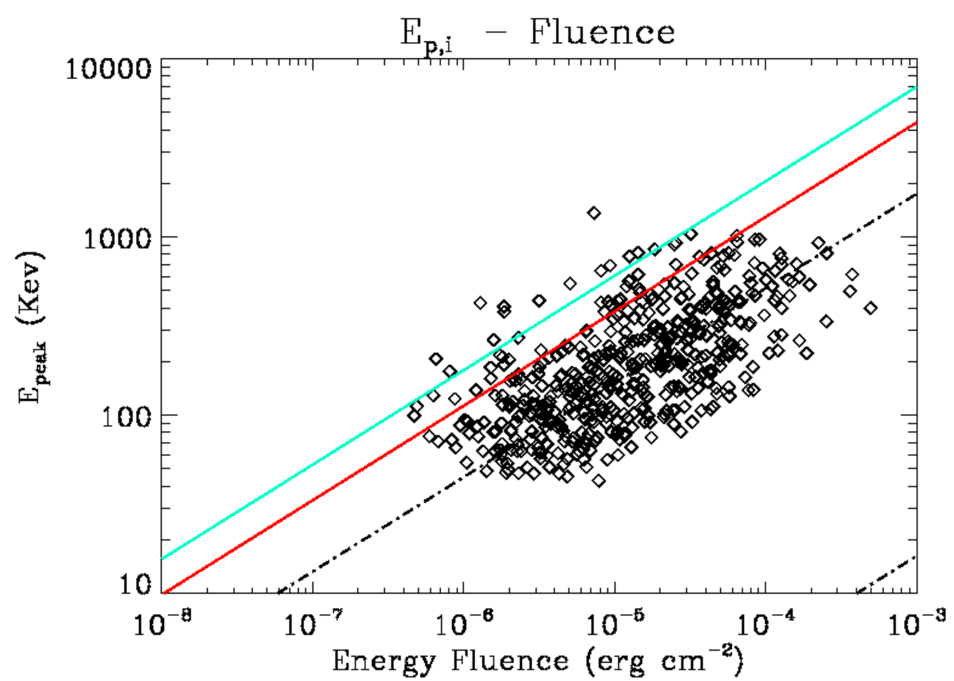




- Amati, Dichiara et al. (2011, in prep.): MC simulations assuming the existence and the measured parameters of the Ep,i – Eiso correlation and accounting for the observed distributions (Eiso, z, Eiso vs. z) and BATSE instrumental sensitivity as a function of Ep (Band 2003-2009)

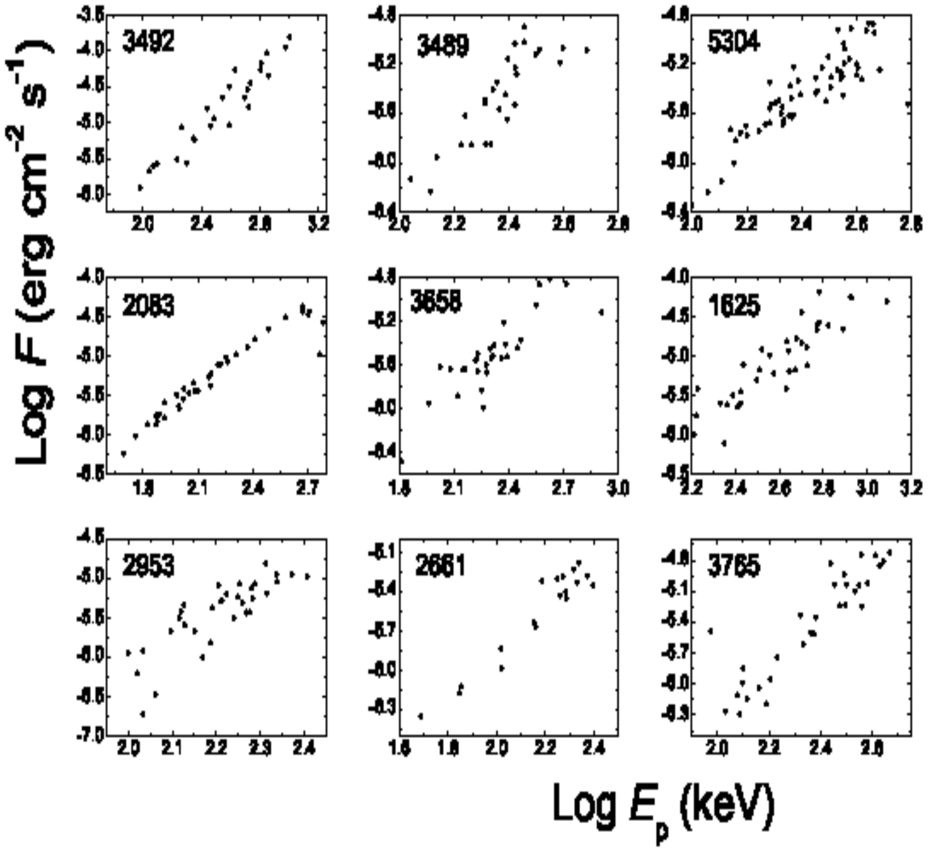
- When accounting for spectral evolution, i.e. Ep = f(Flux), the small fraction of “outliers” in the Ep,obs – Fluence plane is reproduced

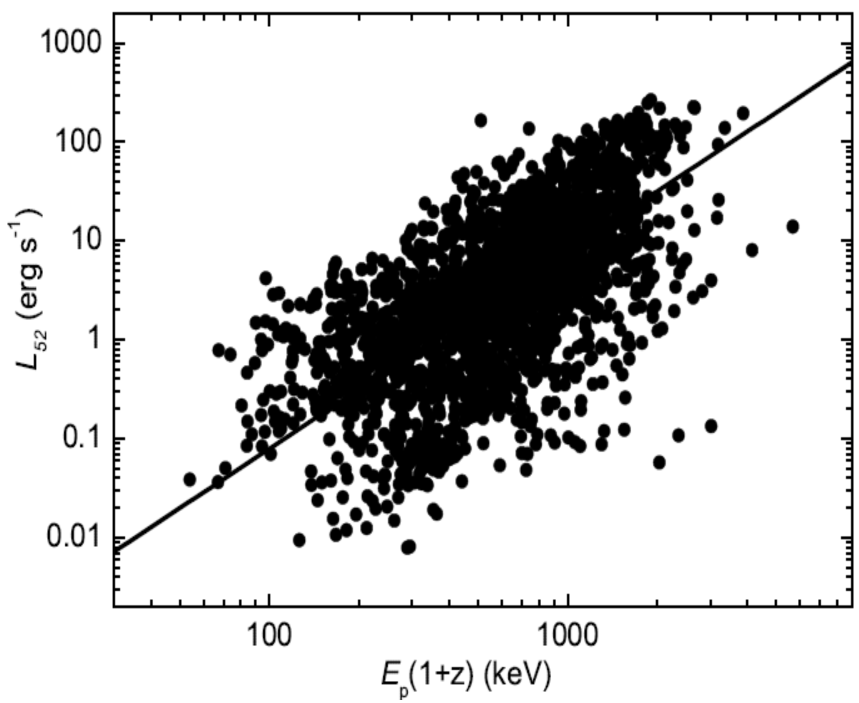




The Ep.i – intensity correlation within single GRBs

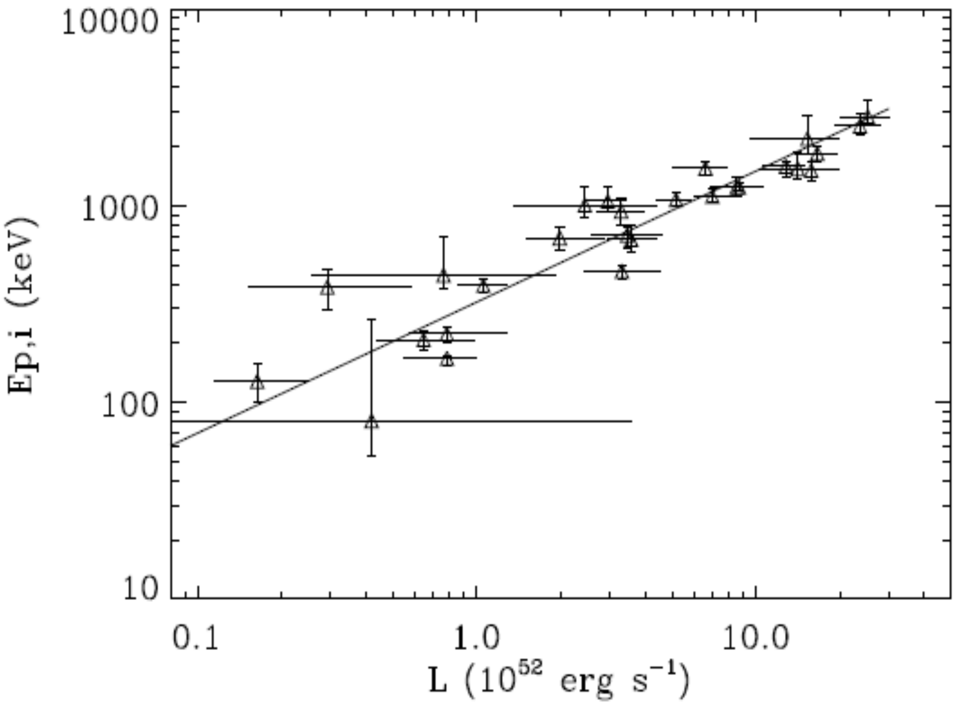
❑ Liang et al.2004: evidence for an Ep – Flux correlation within most BATSE GRBs and, based on pseudo-redshifts, possible existence of a univoque Ep,i(t) – Liso(t) correlation



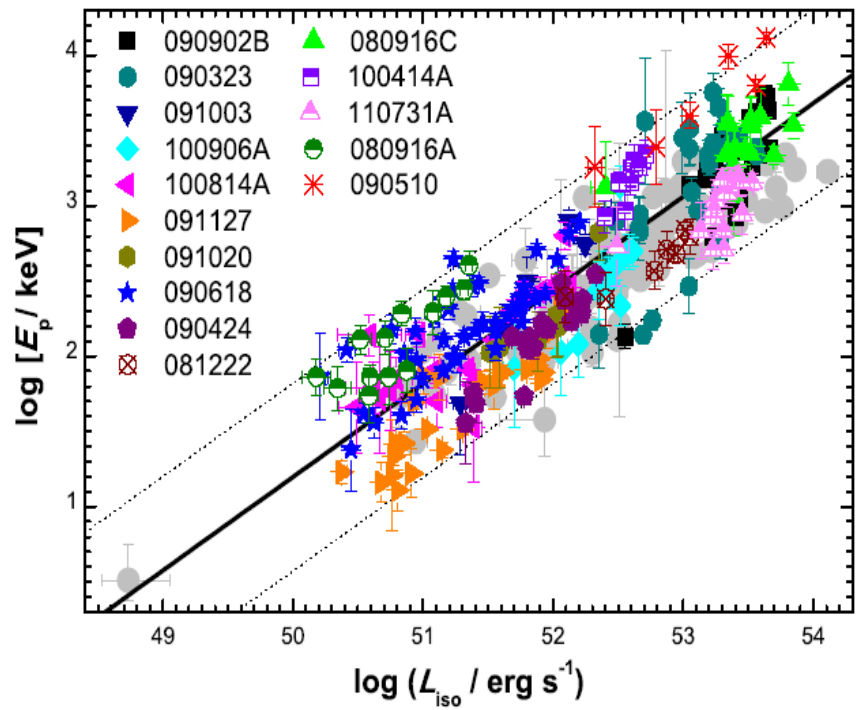


Liang et al., ApJ, 2004

➢ the Ep,i– Liso 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 Ep,i – Intensity correlations and clues to physical explanation**



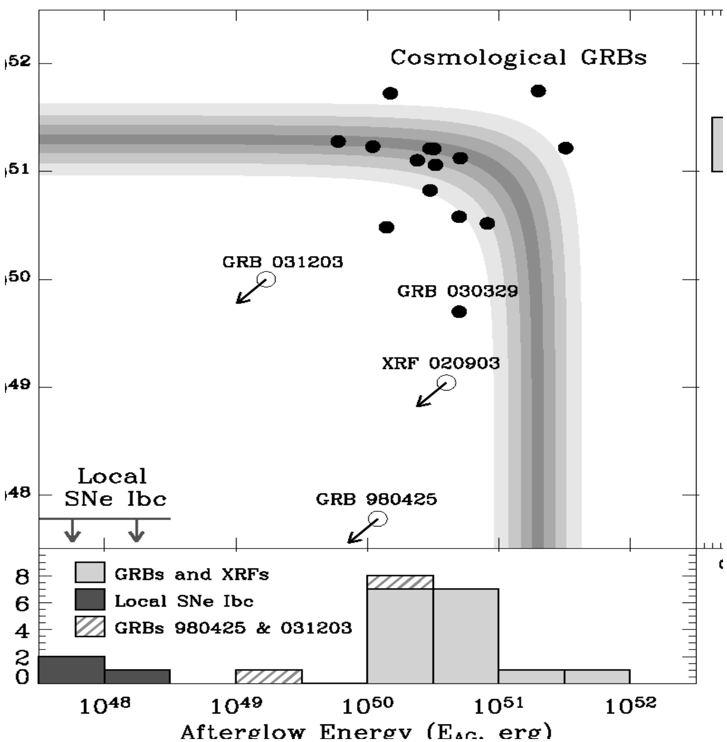
SAX+BATSE (Frontera et al. ApJ, in press)

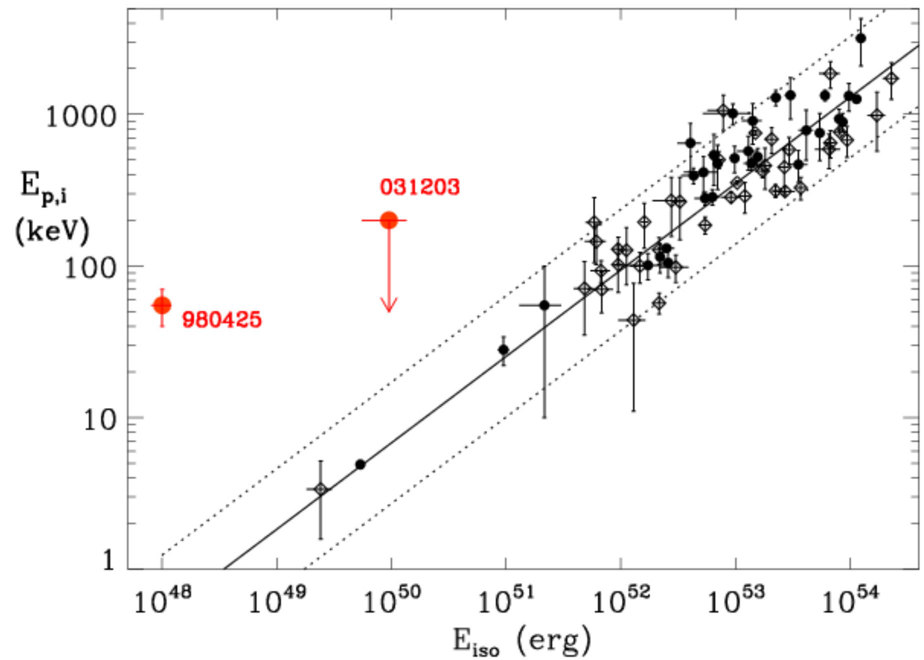


Fermi (e.g., Li et al. , ApJ, 2012)

Outliers ?

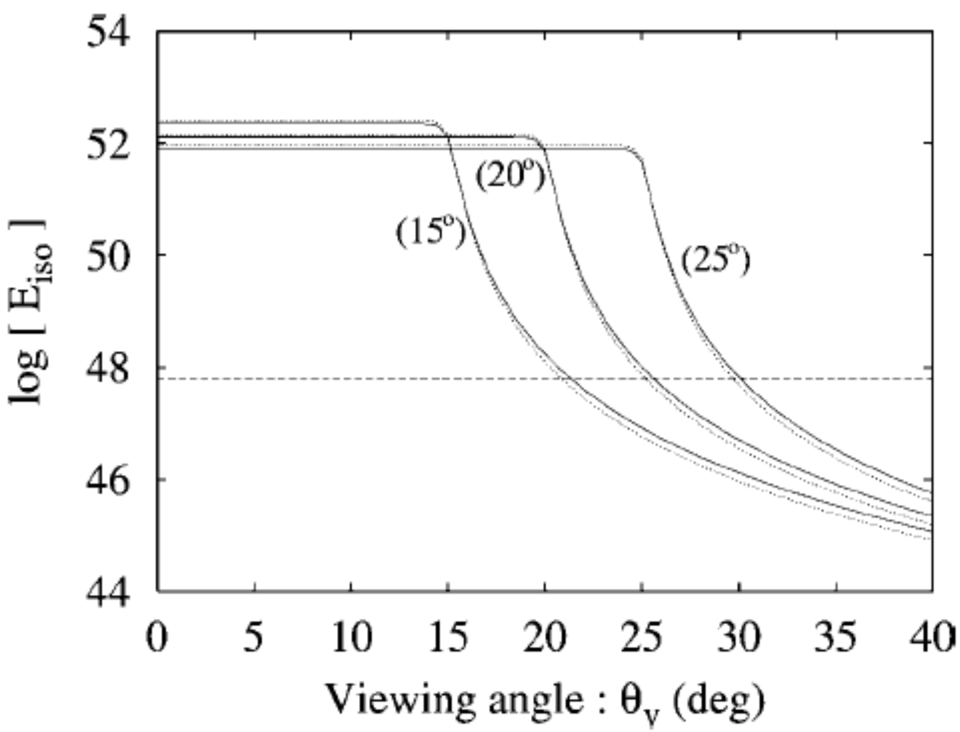
- GRB980425 not only prototype event of GRB/SN connection but closest GRB (z = 0.0085) and sub-energetic event (Eiso ~ 10^{48} erg, Ek,aft ~ 10^{50} erg)
- GRB031203: the most similar case to GRB980425/SN1998bw: very close (z = 0.105), SN2003lw, sub-energetic



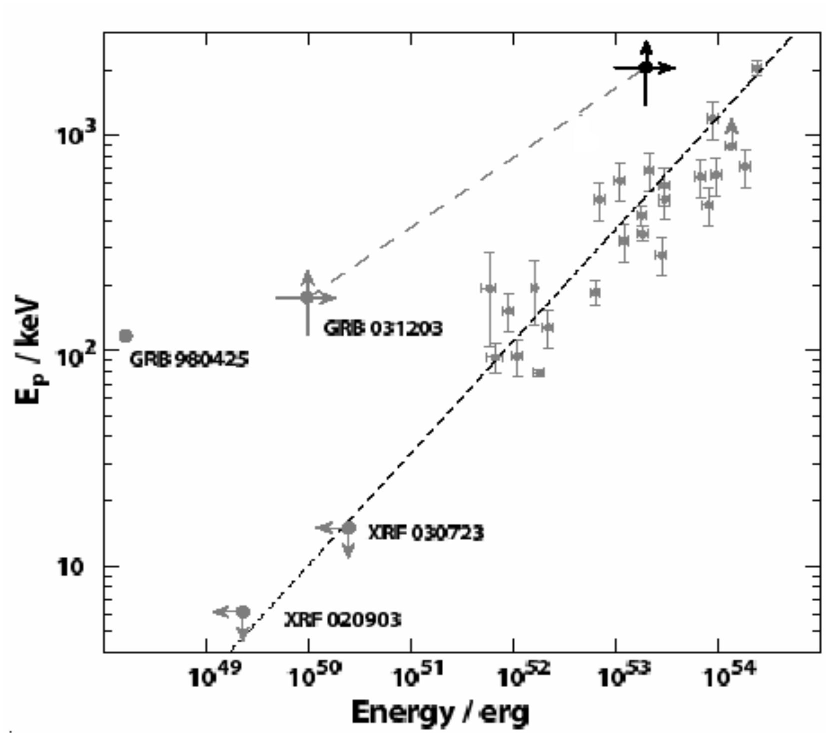


- the most common explanations for the (apparent ?) sub-energetic nature of GRB980425 and GRB031203 and their violation of the Ep,i – Eiso correlation assume that they are NORMAL events seen very off-axis (e.g. Yamazaki et al. 2003, Ramirez-Ruiz et al. 2005)
- $\delta=[\gamma(1-\beta\cos(\theta v-\Delta\theta))]^{-1}$, $\Delta Ep \propto \delta$, $\Delta Eiso \propto \delta^{(1+\alpha)}$

  $\alpha=1\div2.3$ -> $\Delta Eiso \propto \delta^{(2\div3.3)}$



Yamazaki et al., ApJ, 2003

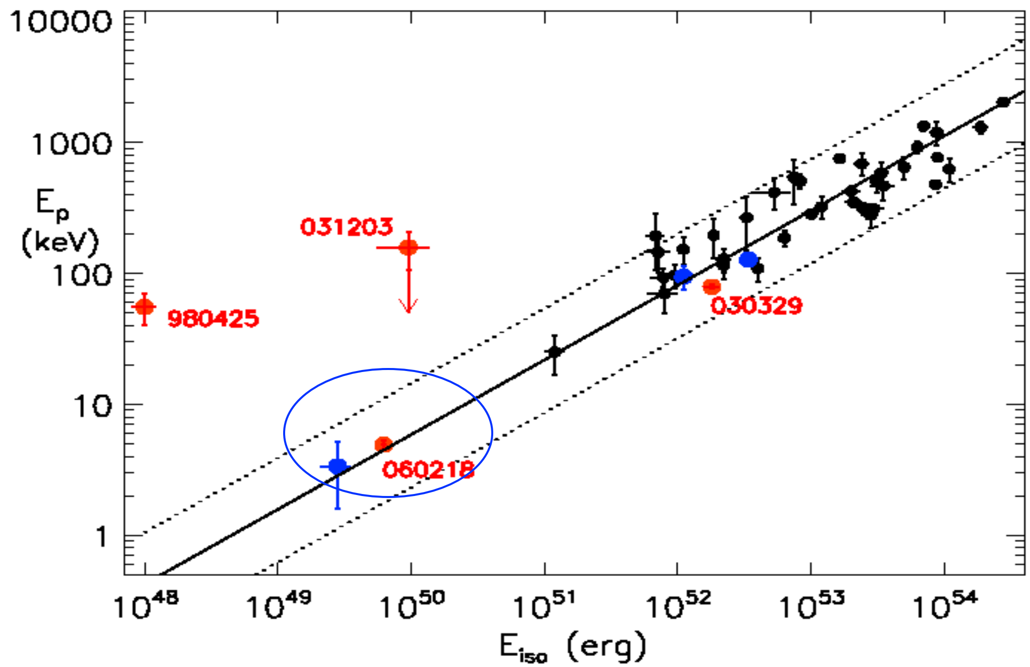


Ramirez-Ruiz et al., ApJ, 2004

- GRB 060218, a very close (z = 0.033, second only to GRB9809425), with a prominent association with SN2006aj, and very low Eiso (6×10^{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

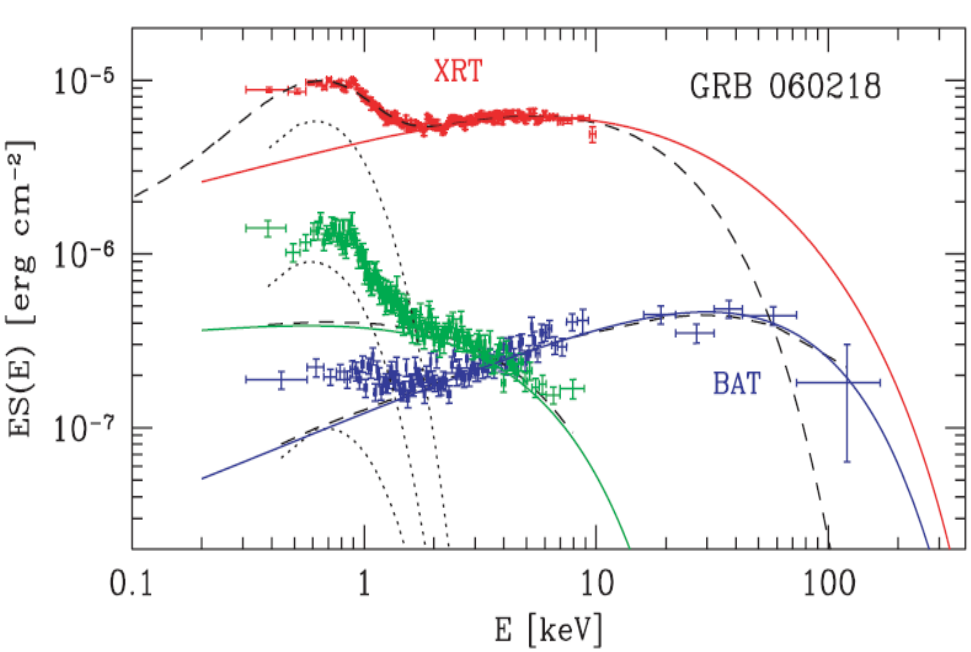


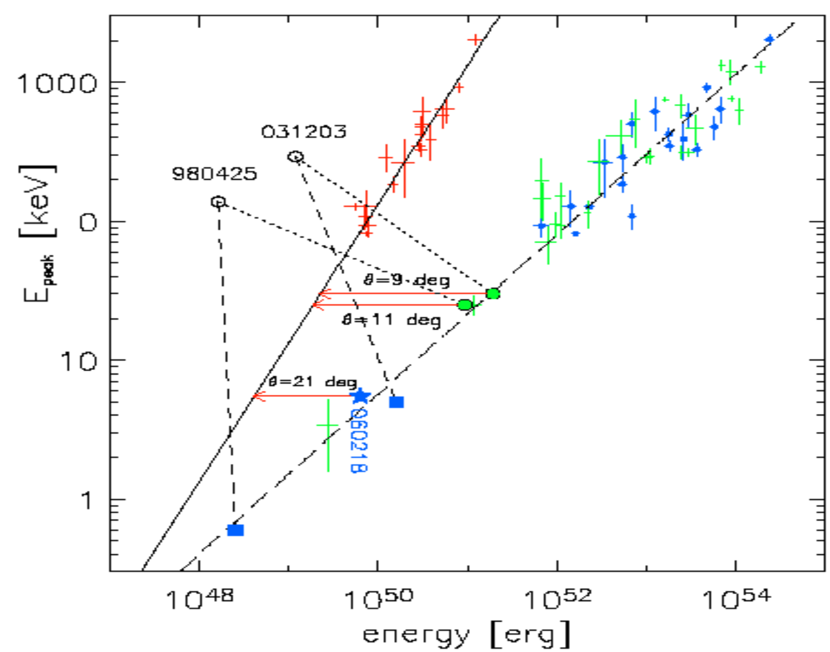
Amati et al., 2007

- GRB060218 was a very long event (~3000 s) and without XRT mesurement (0.3-10 keV) Ep,i would have been over-estimated and found to be inconsistent with the Ep,i-Eiso 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 Ep,i-Eiso correlation

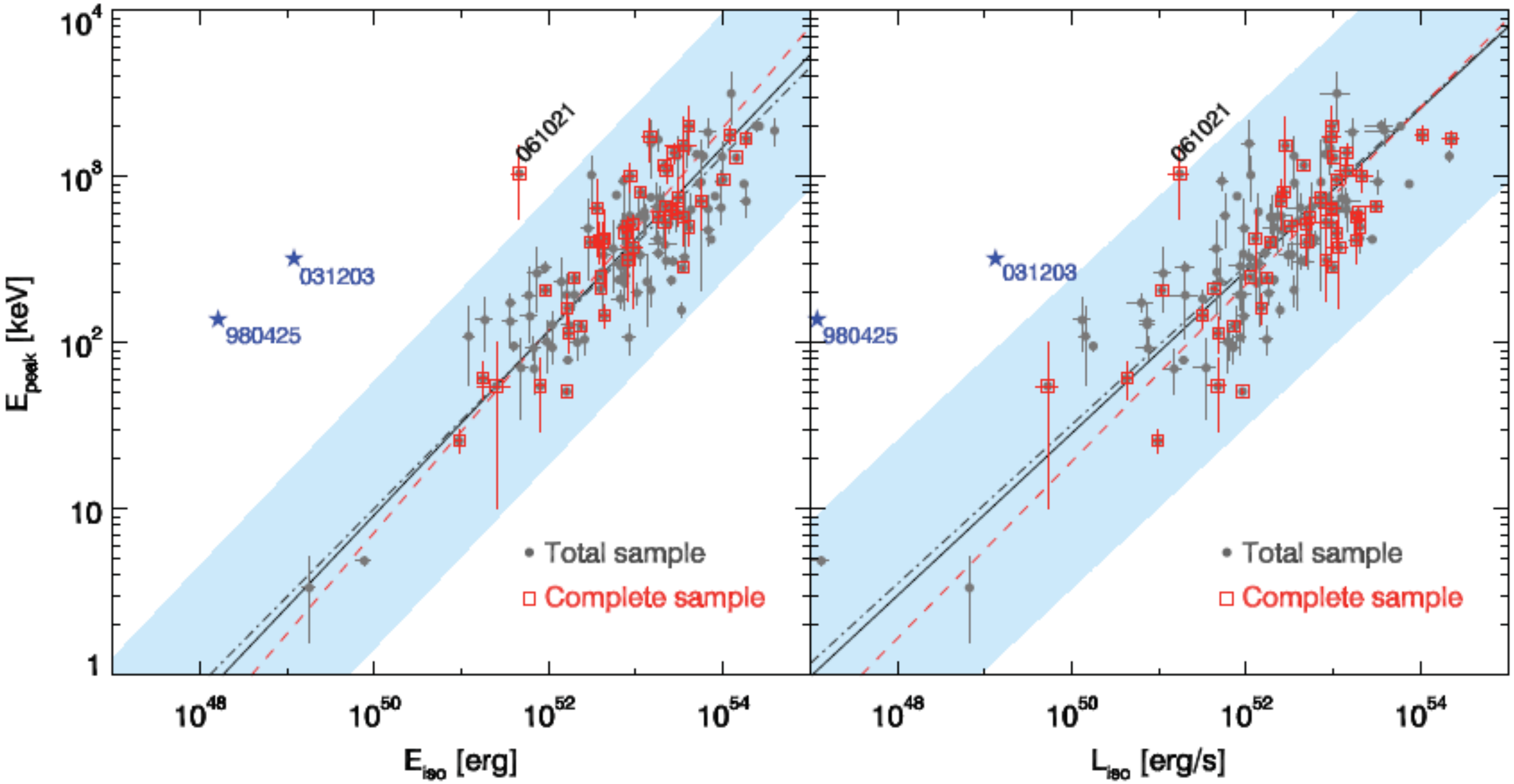
- sub-energetic GRB consistent with the correlation; apparent outliers(s) GRB 980425 (GRB 031203) could be due to viewing angle or instrumental effect





❑ Nava et al. 2012: Ep,i – Eiso and Ep – Lp,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

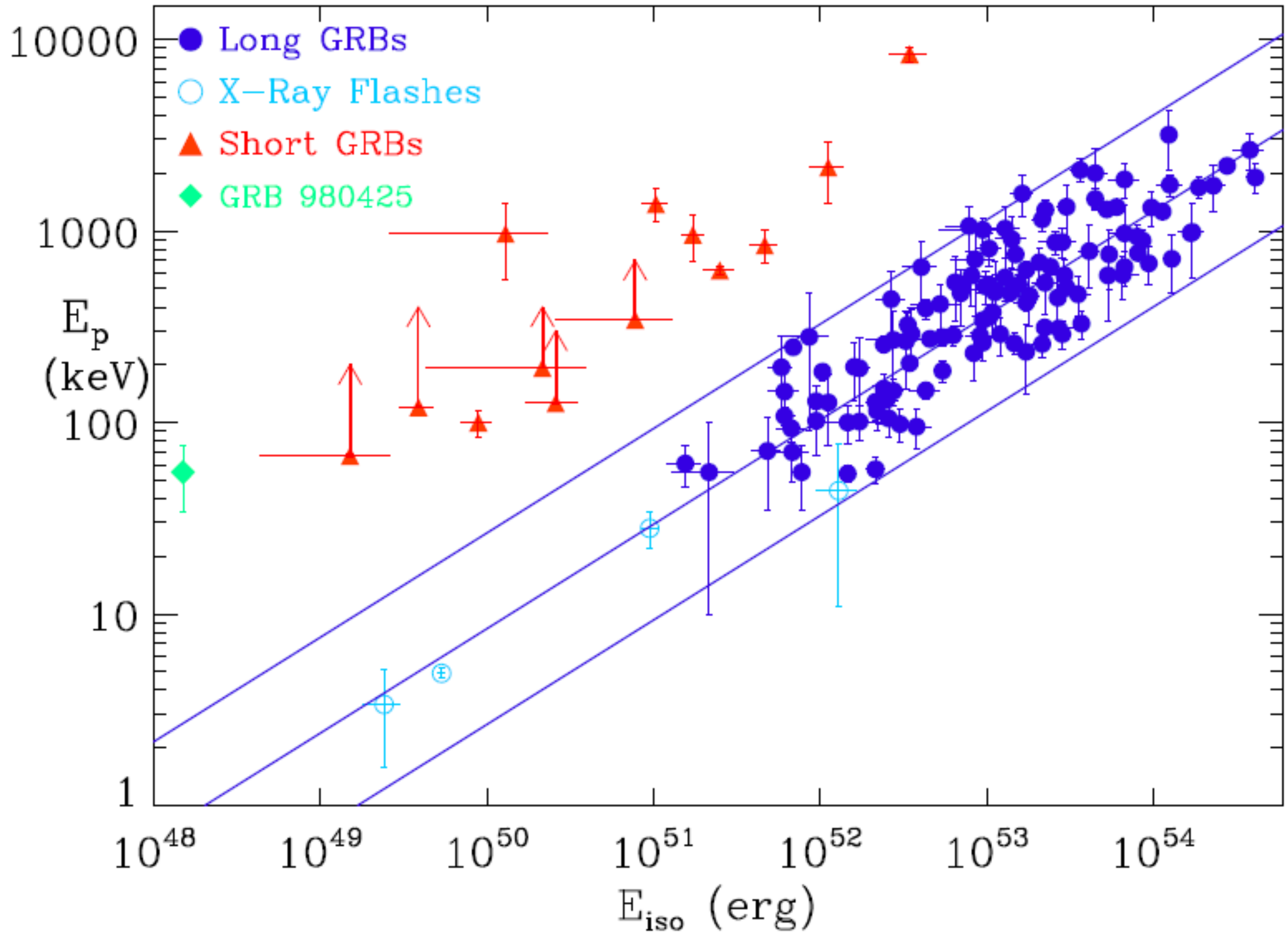
❑ GRB 061021 possible outlier, but Ep based on Konus-WIND analysis of only the first hard pulse -> need time-averaged spectral analysis including long soft tail for reliable Ep estimate



Nava et al. 2012, "complete sample of Salvaterra et al. 2011"

➢ *identifying and understanding sub-classes of GRBs*

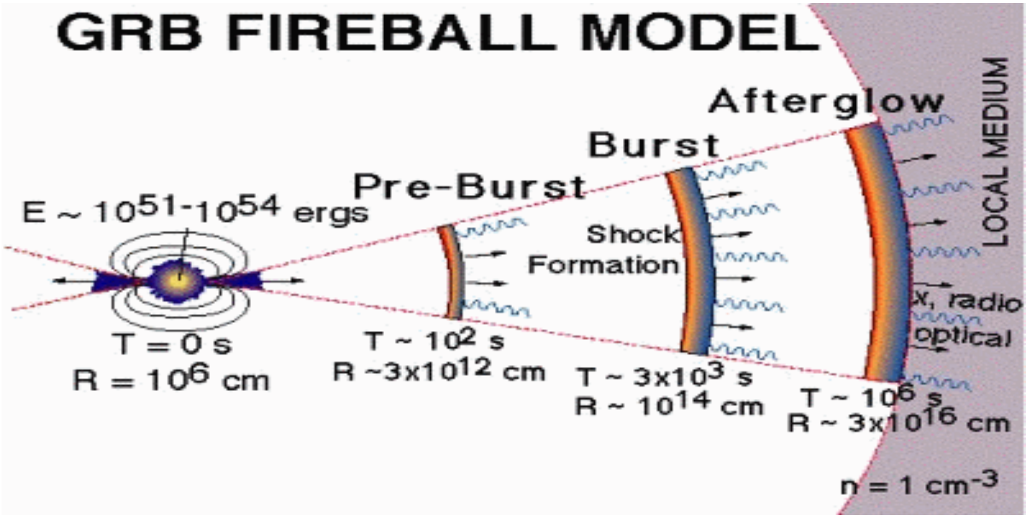
➢ Up to date (Sept. 2012) Ep,i – Eiso plane: 148 long GRBs, 4 XRFs, 13 short GRBs

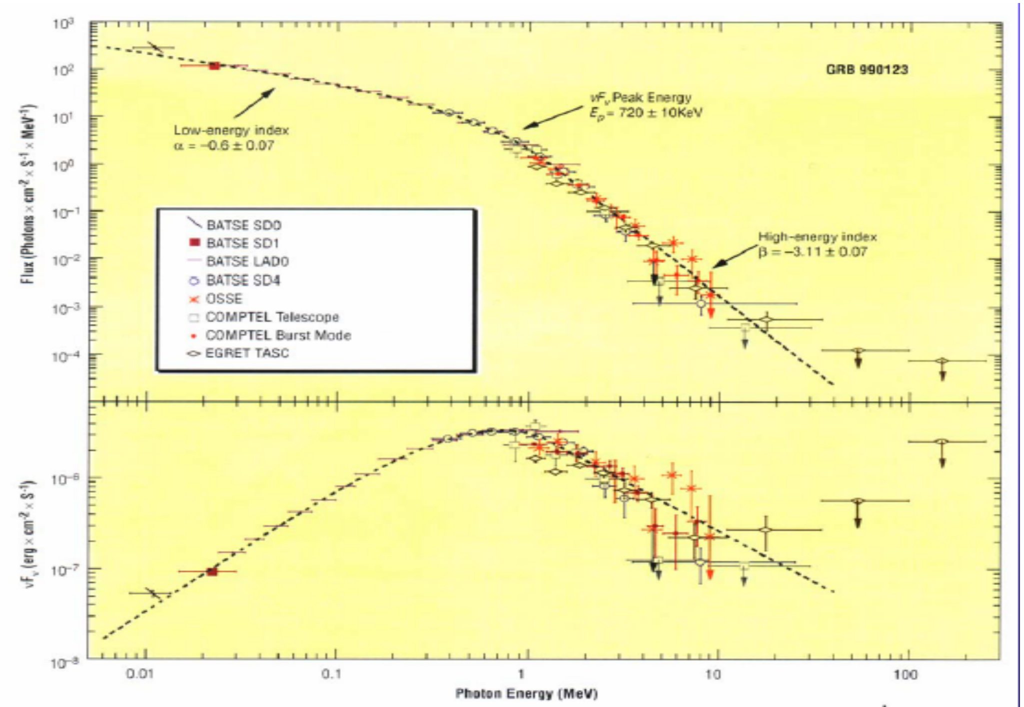


Implications of the Ep,i – intensity correlation

➢ *GRB prompt emission physics*

❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy dominated fireball , poynting flux dominated fireball)

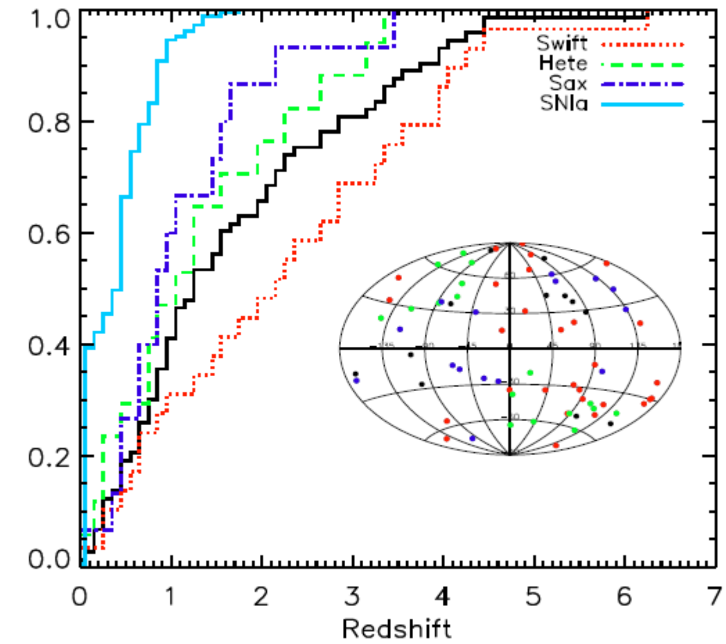


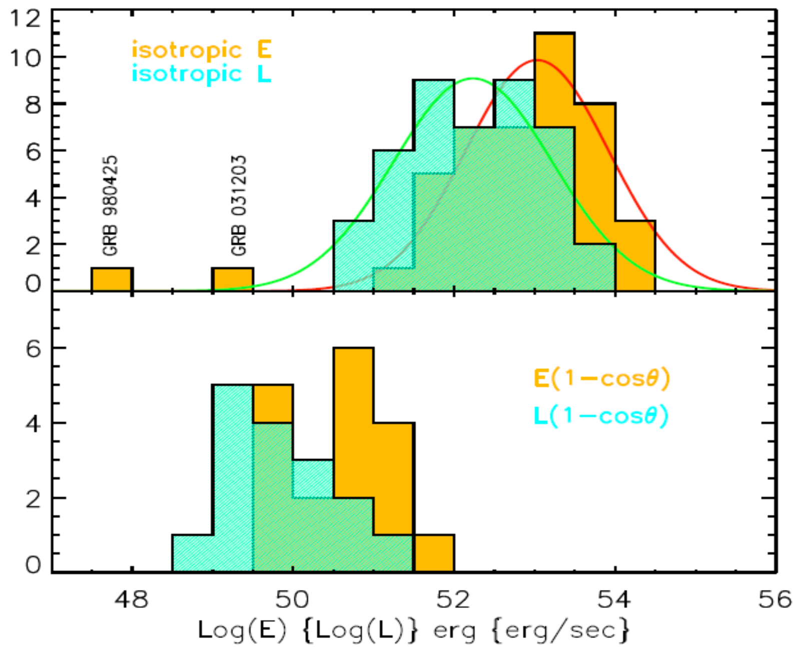


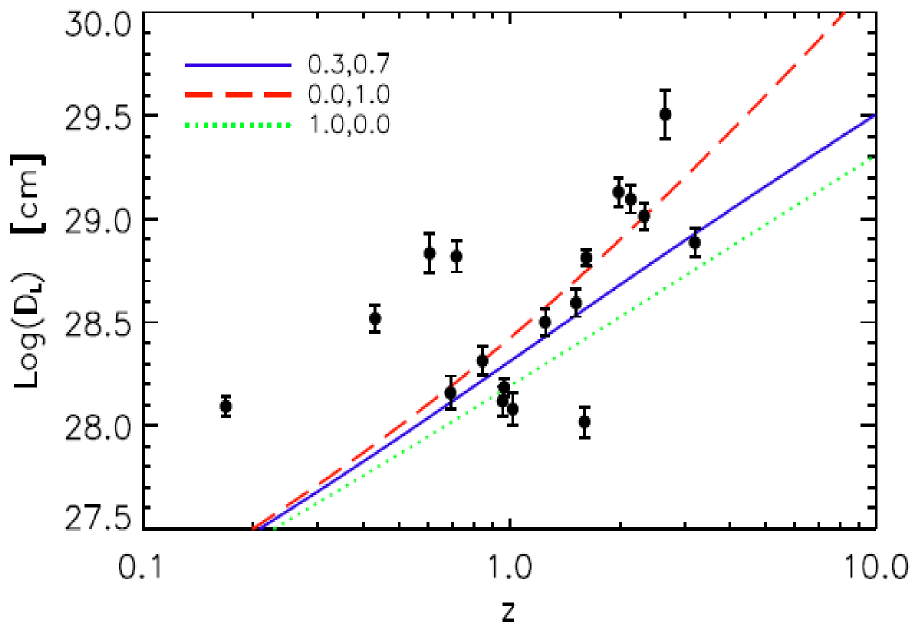
- **Addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions **and substantially reduces the number of GRB that can be used (e.g., #$E_{p,i}$ – E_{γ} ~ ¼ #$E_{p,i}$ – E_{iso})**

- **Amati et al. 2008 (and many others afterwards): let's make a step backward and focus on the "simple" Ep,i – Eiso (Ep,i - Liso) correlation**

- 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