The $E_{p,i}$ – intensity correlation in GRBs

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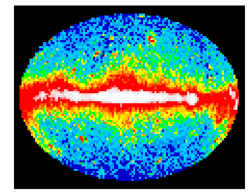
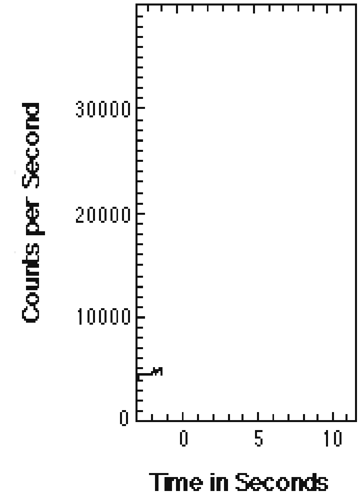
Outline

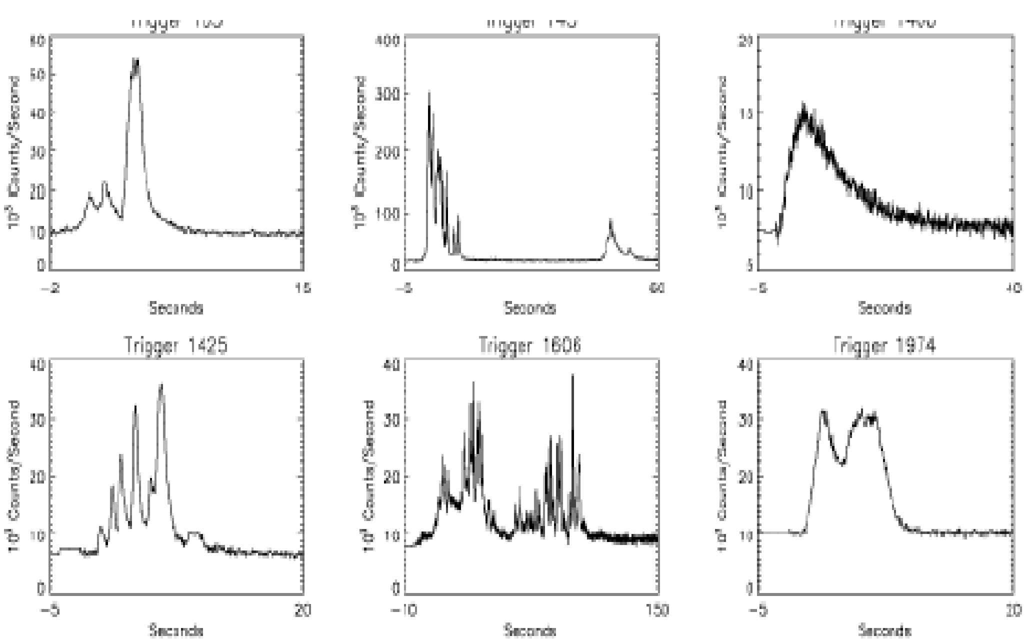
- Gamma-Ray Bursts: very short introduction
- The spectral peak photon energy: Ep
- The Ep,i – Eiso correlation
- Other Ep,i – Intensity correlations
- Implications and uses of the Ep,i – Intensity correlation
- Instrumental / selection effects, systematics, outliers
- Conclusions and perspectives

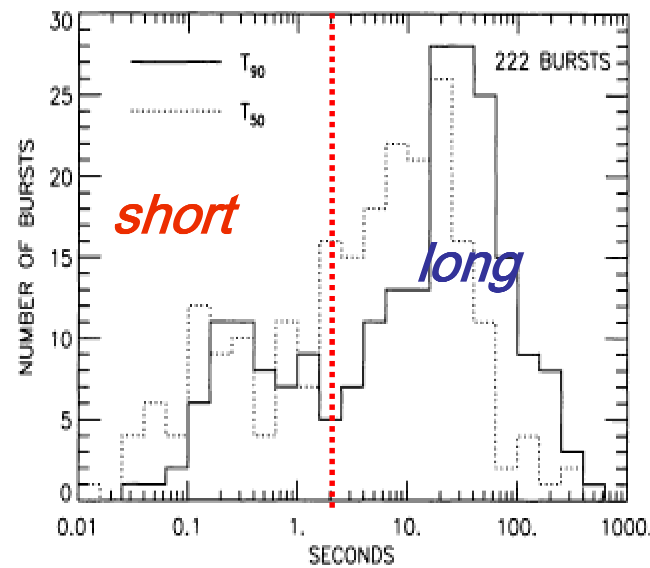
The Gamma-Ray Burst phenomenon

- 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



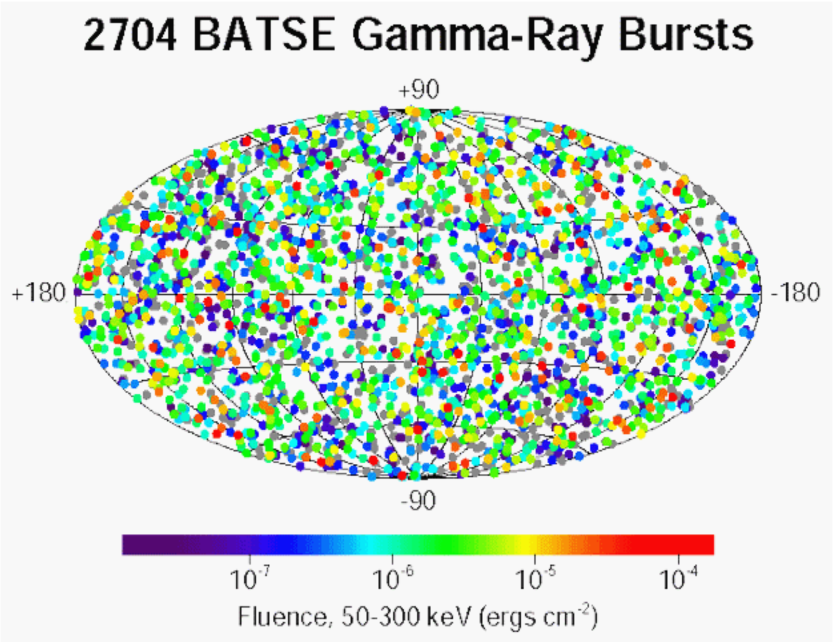


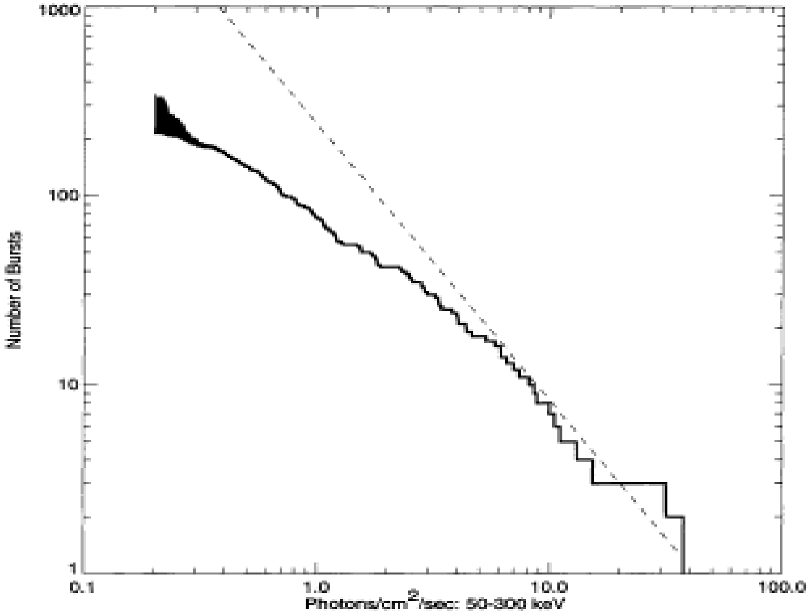




Early evidences for a cosmological origin of GRBs

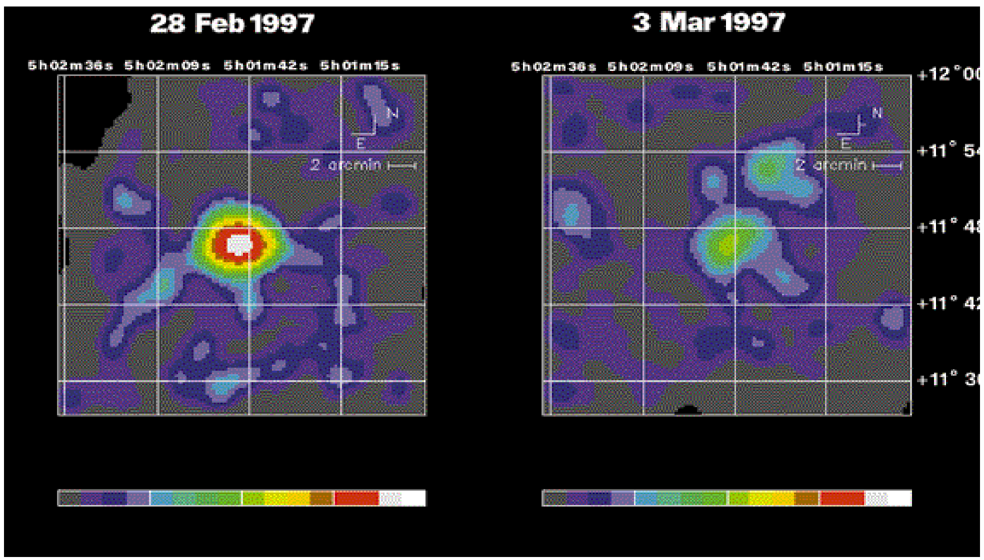
- ❑ isotropic distribution of GRBs directions
- ❑ paucity of weak events with respect to homogeneous distribution in euclidean space
- ❑ **given the high fluences (up to more than 10^{-4} erg/cm2 in 20-1000 keV) a cosmological origin would imply huge luminosity**
- ❑ thus, a "local" origin was not excluded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

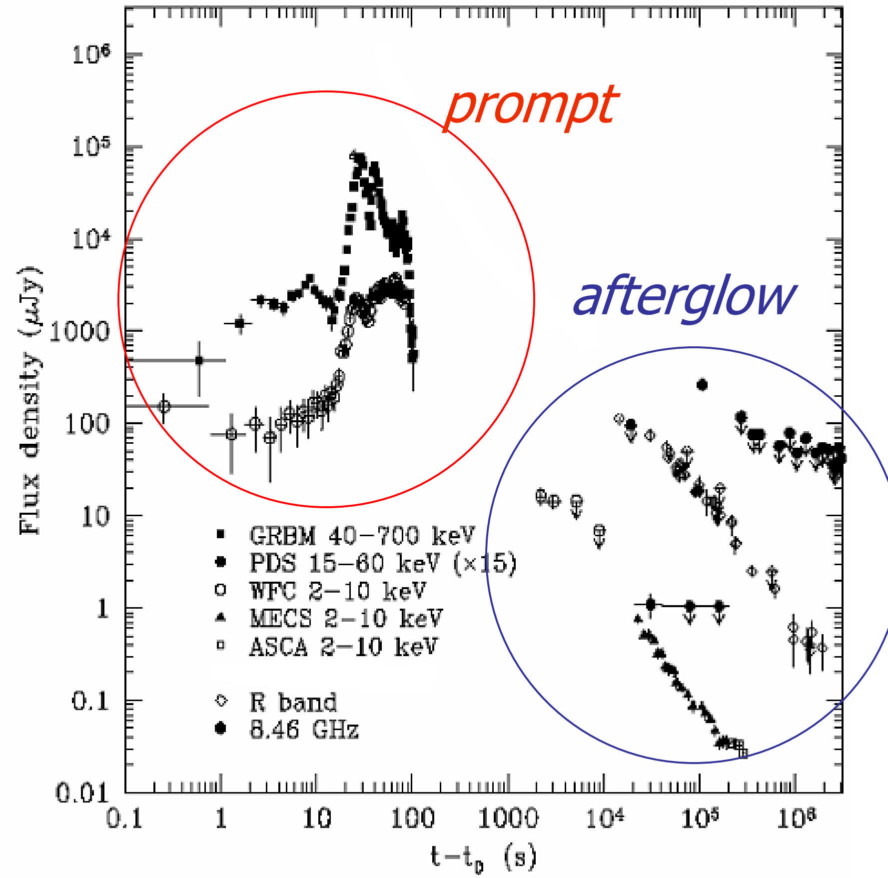




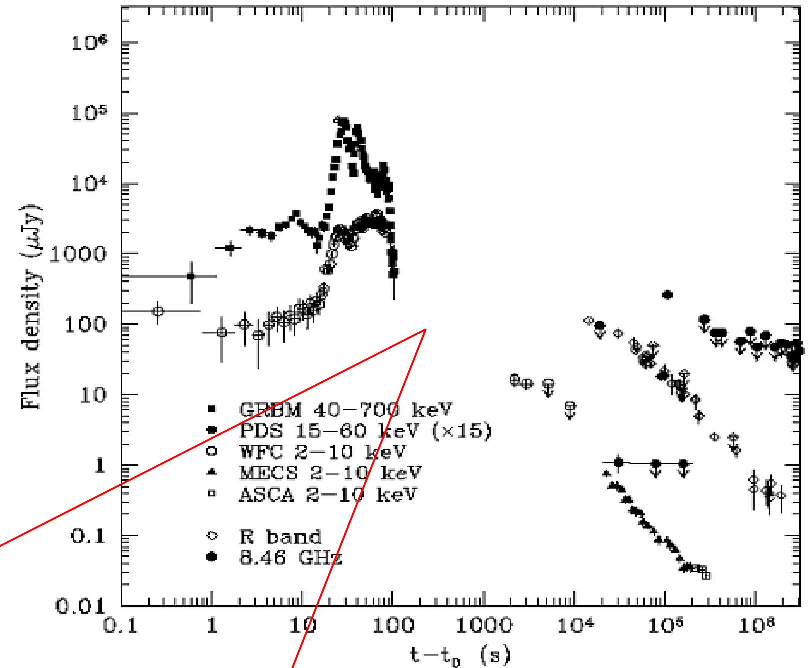
Establishing the GRBs cosmological distance scale

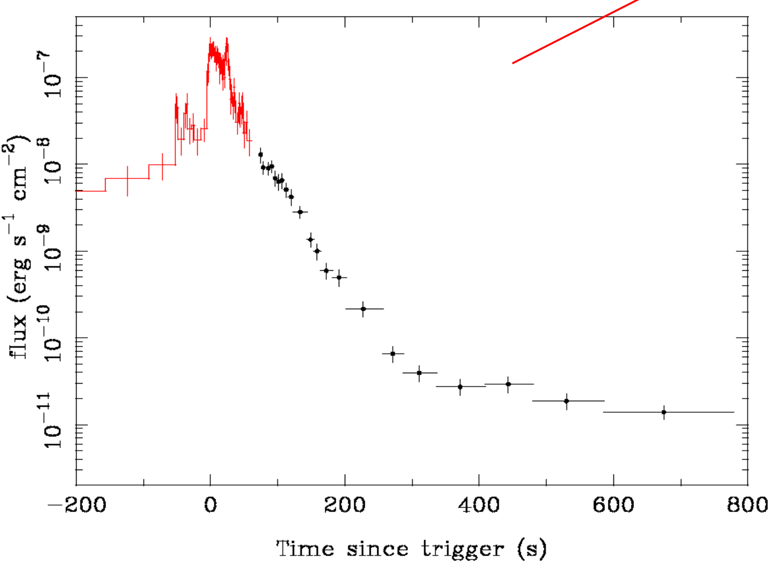
❑ in 1997 discovery of afterglow emission by BeppoSAX



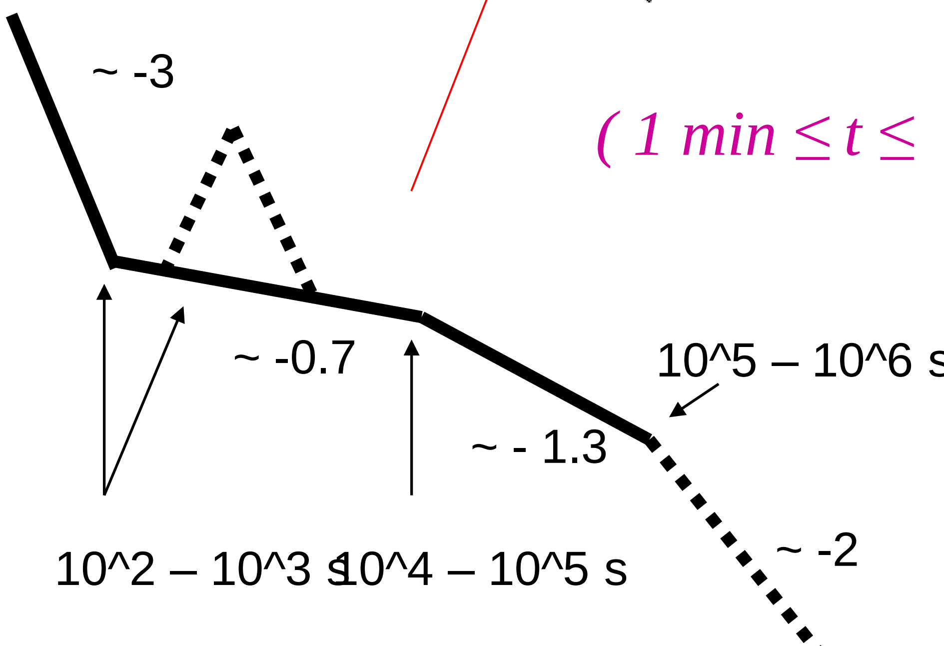


❑ (observational gap between "prompt" and "afterglow emission" will be filled by Swift in > 2004)





Swift team

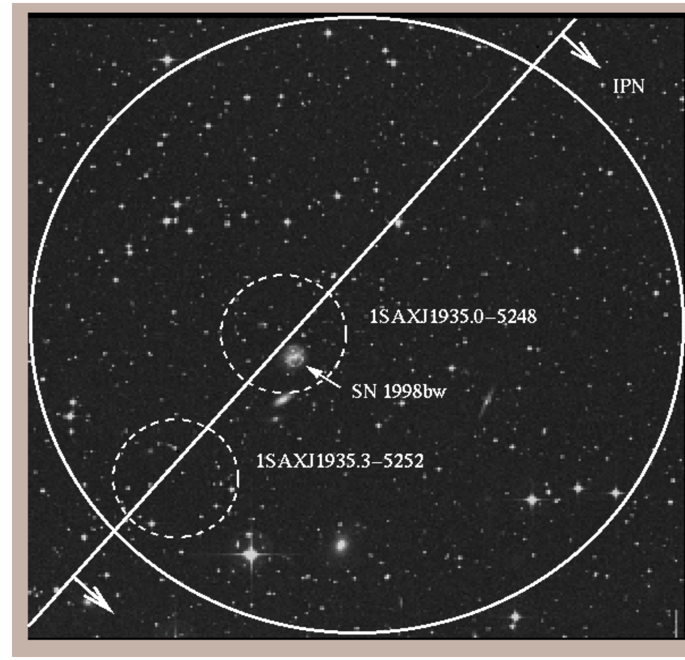


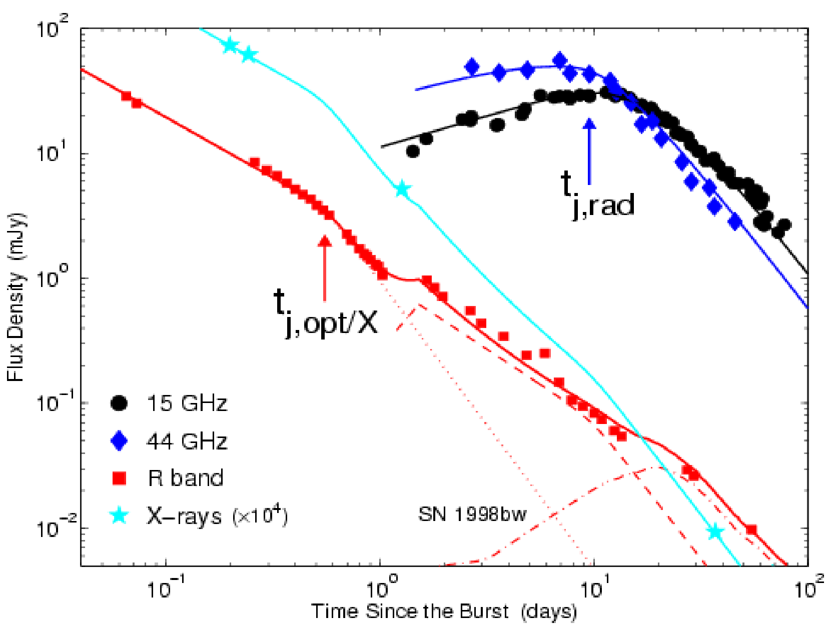
(1 min ≤ t ≤ hours)

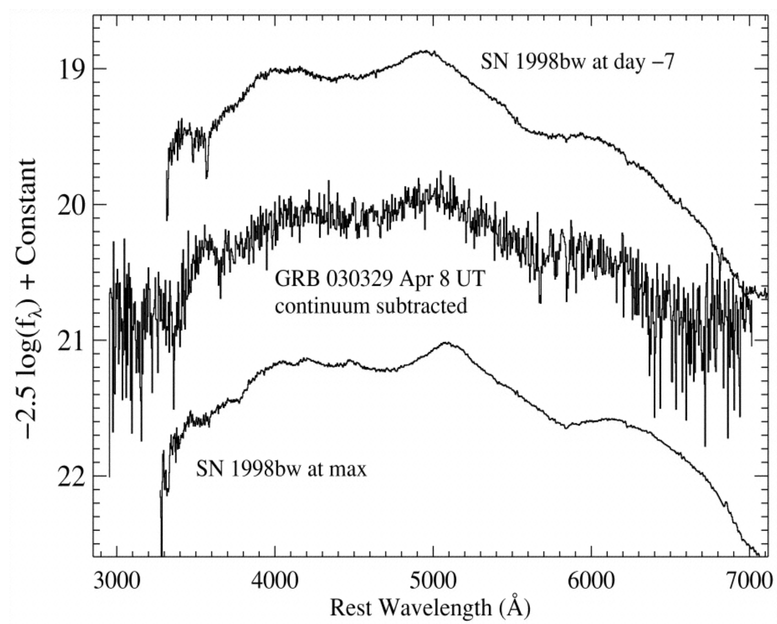
1997: accurate (a few arcmin) and quick localization of X-ray afterglow -> optical follow-up -> first optical counterparts and host galaxies -> **GRB-SN connection**:

- GRB 980425, a normal GRB detected and localized by WFC and NFI, but in temporal/spatial coincidence with a type Ib/c SN at z = 0.008

- bumps in optical afterglow light curves and optical spectra resembling that of GRB980425



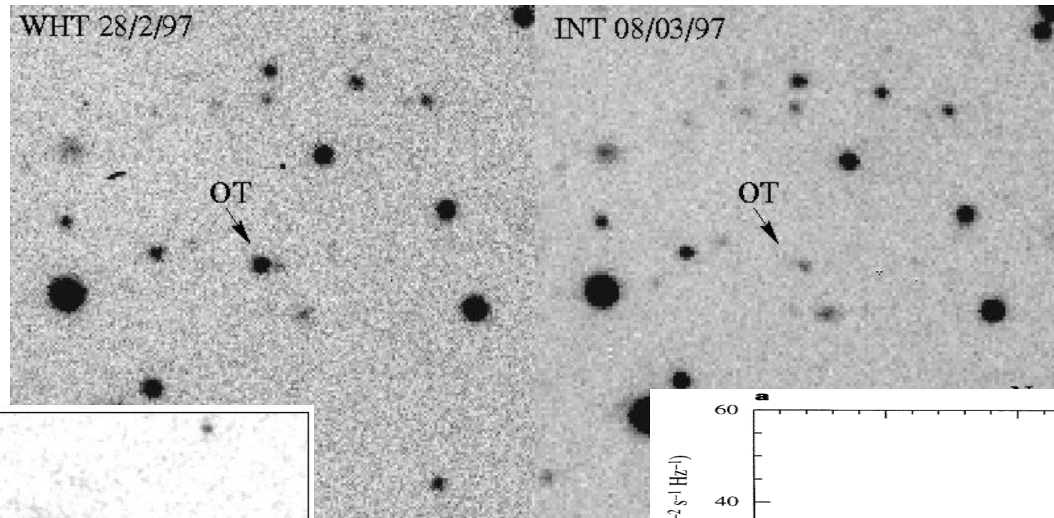


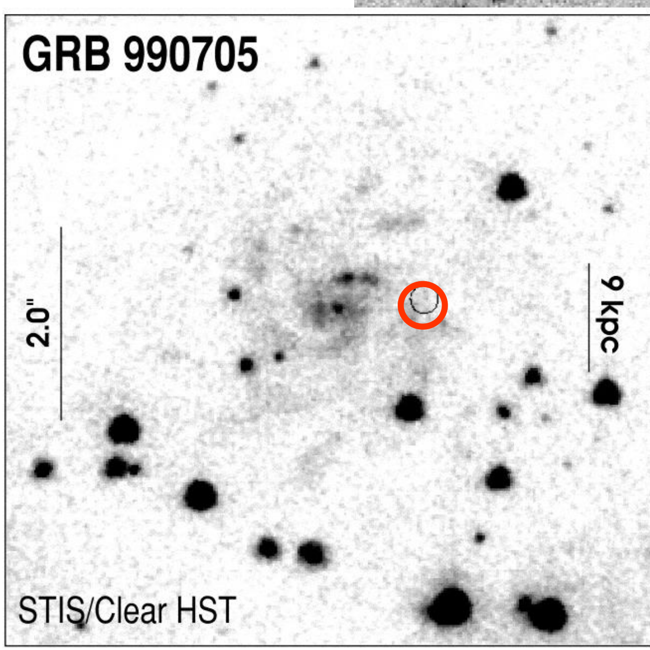


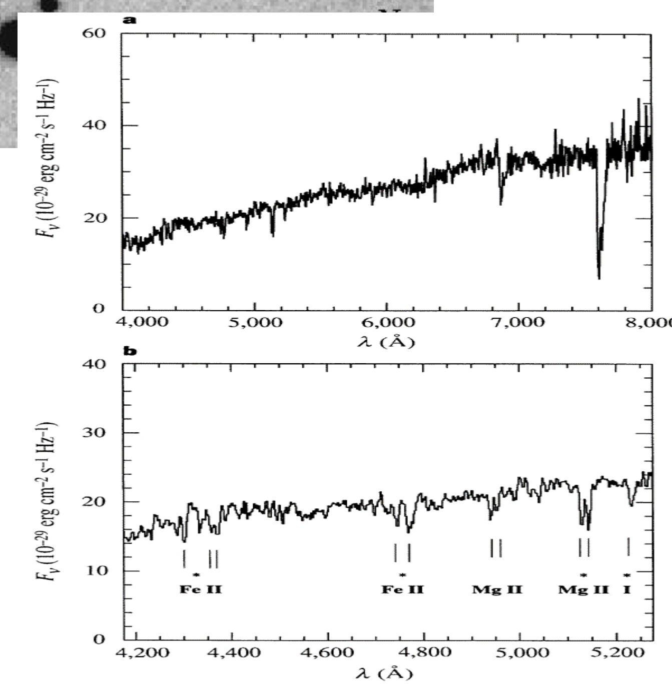
Galama et al. 1998, Hjorth et al. 2003

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

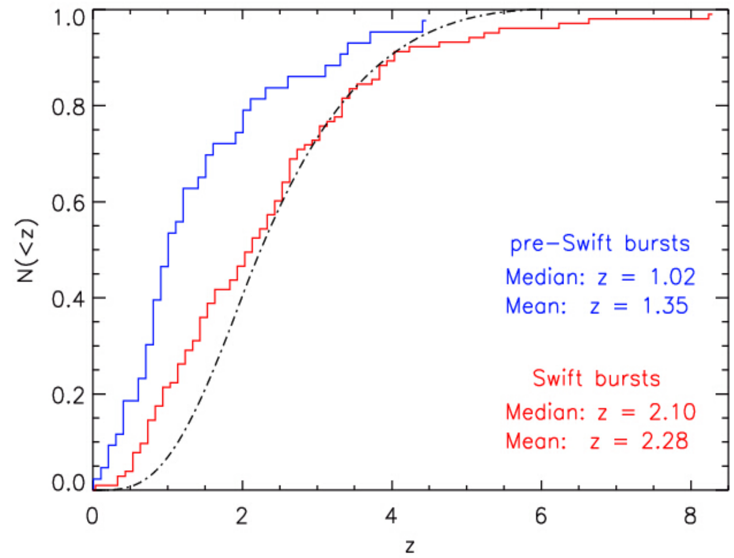
❑ optical spectroscopy of afterglow and/or host galaxy –> first measurements of GRB redshift

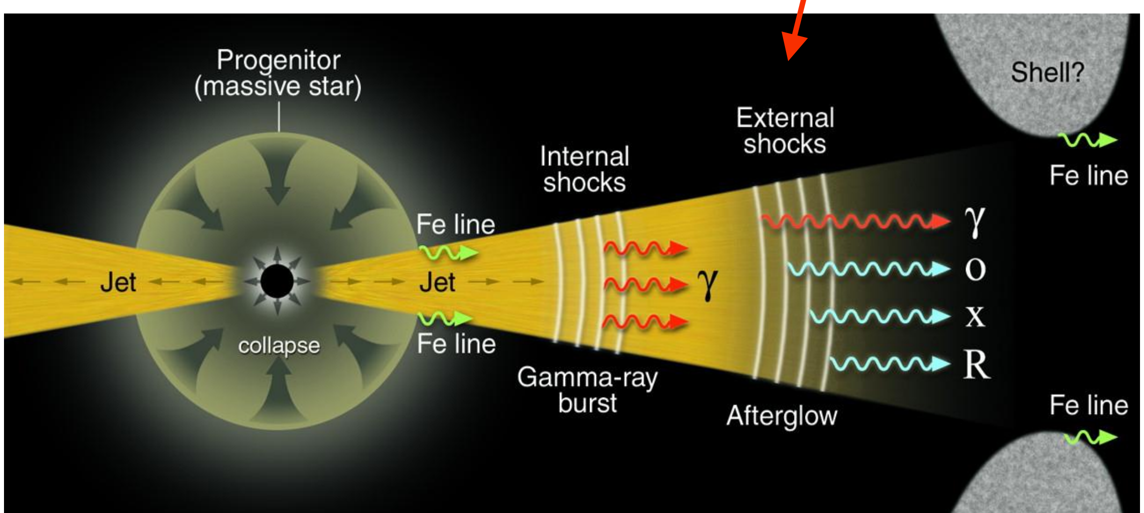


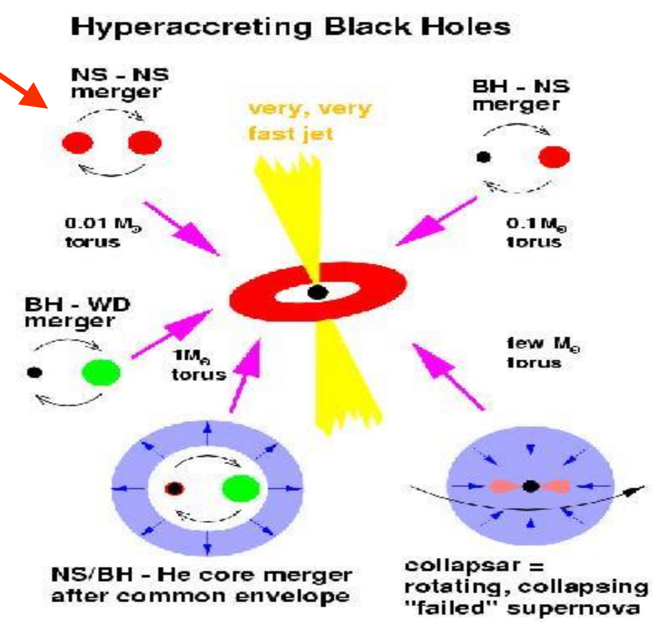




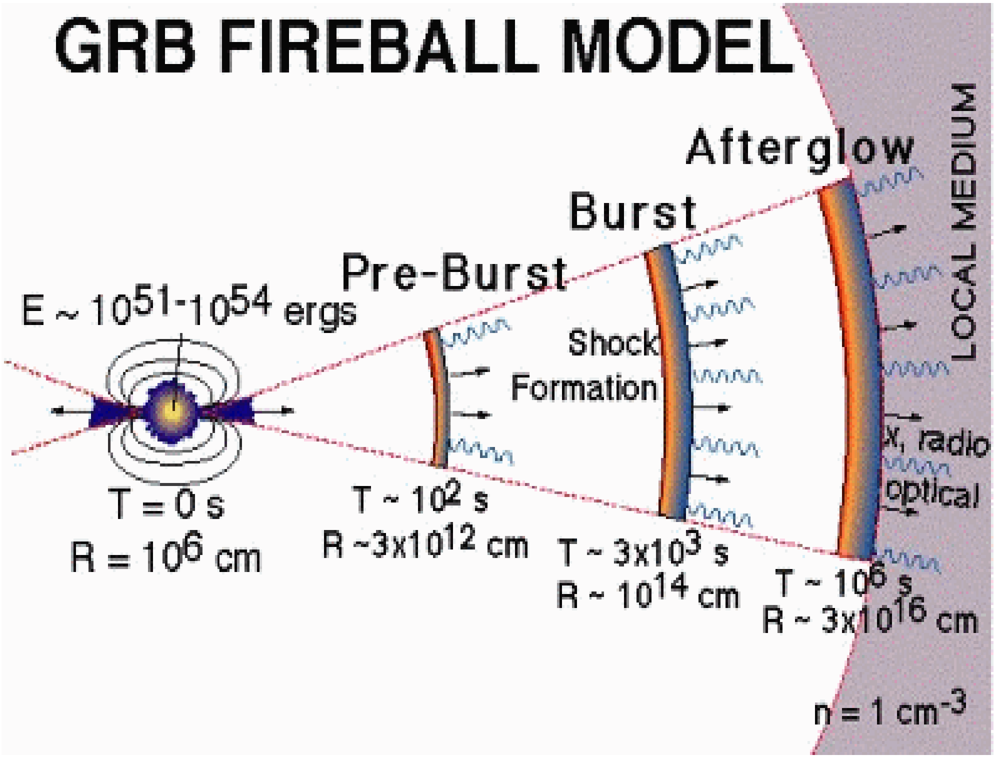
- ➢ **redshifts higher than 0.01 and up to > 8: GRB are cosmological !**
- ➢ **their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s !)**
- ➢ fundamental input for origin of long / short

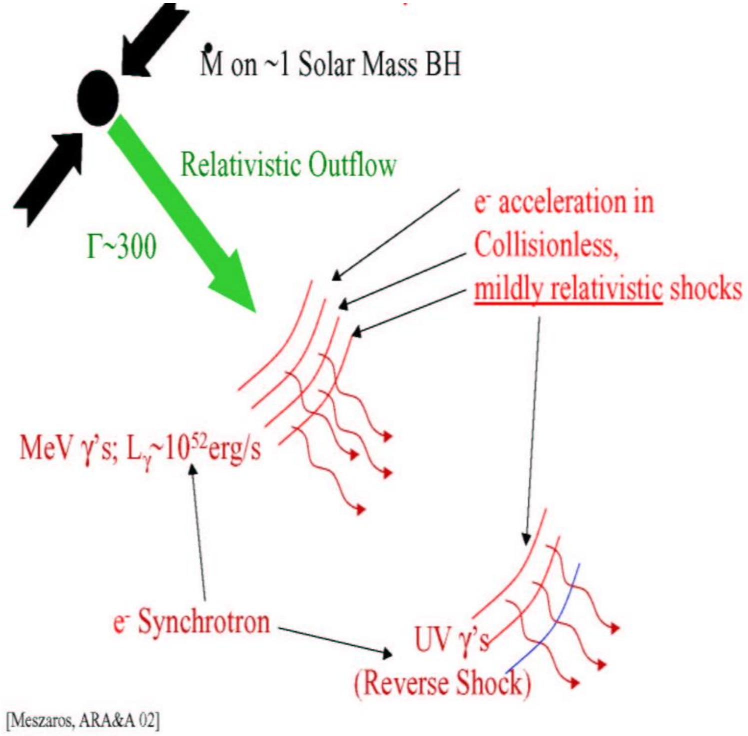






Standard scenarios for GRB phisics

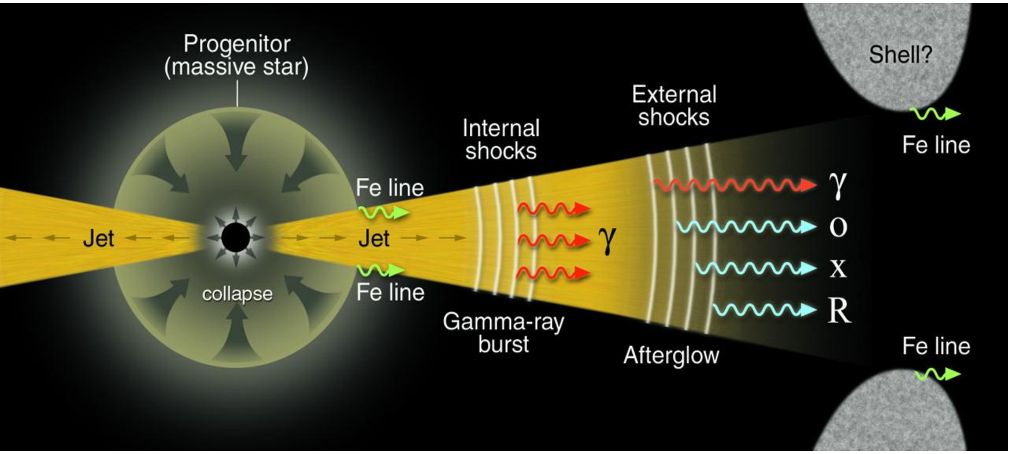




- ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic (Γ > 100) expansion (fireball or firejet)
- non thermal spectra -> shocks synchrotron emission (SSM)
- fireball internal shocks -> prompt emission
- fireball external shock with ISM -> afterglow emission

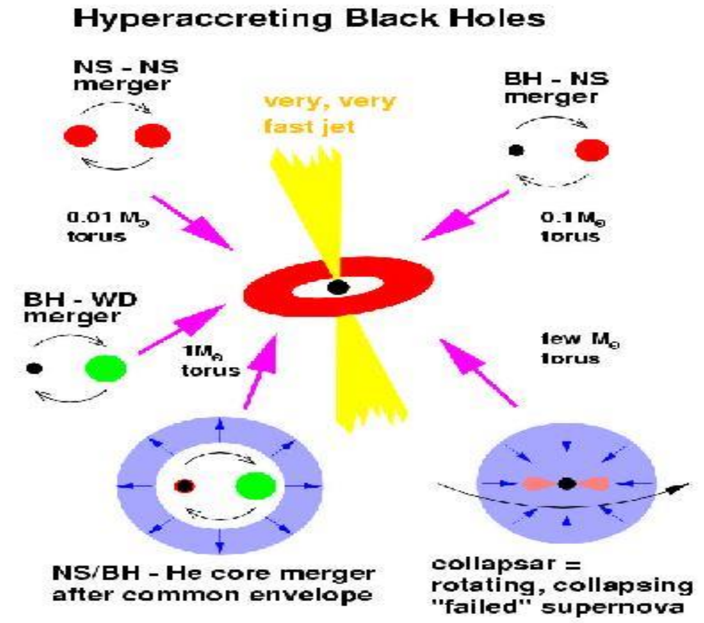
Standard scenarios for GRB progenitors

LONG



- energy budget up to >10^{54} erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

SHORT



- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

The spectral peak photon energy: Ep

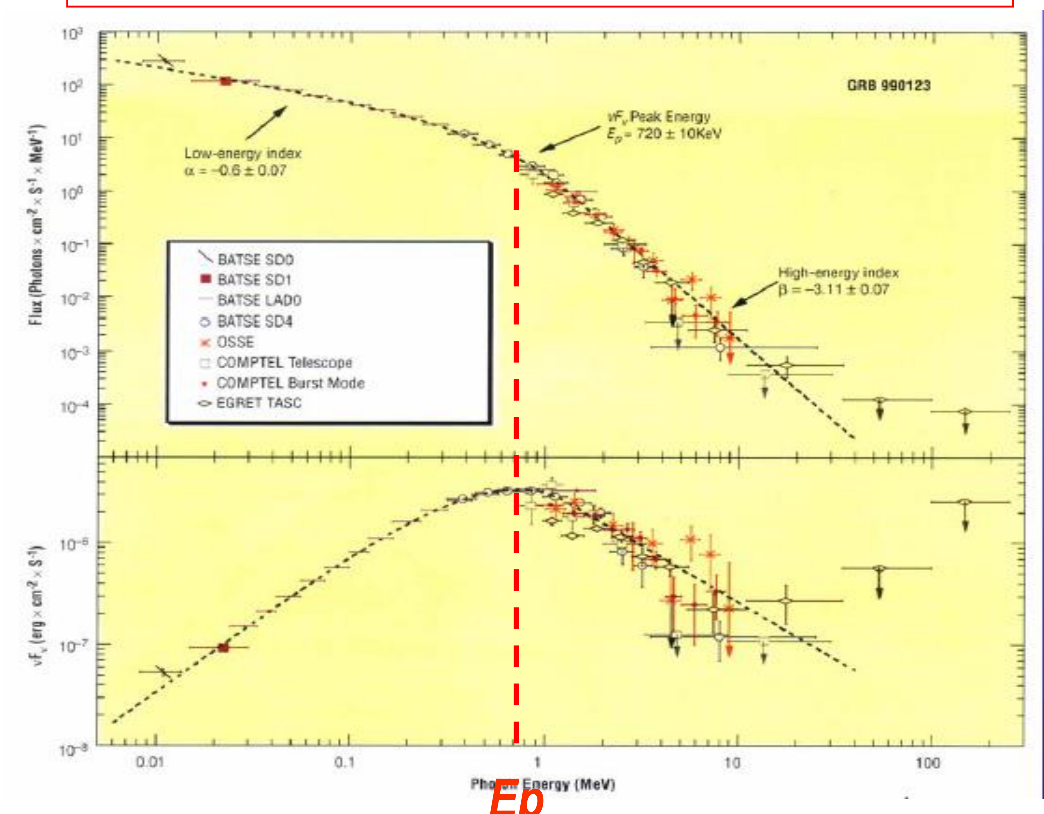
➢ GRB spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy

$$N_E(E) = A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left(-\frac{E}{E_0}\right),$$

$$(\alpha - \beta)E_0 \geq E$$

$$= A\left[\frac{(\alpha-\beta)E_0}{100\ \mathrm{keV}}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta},$$

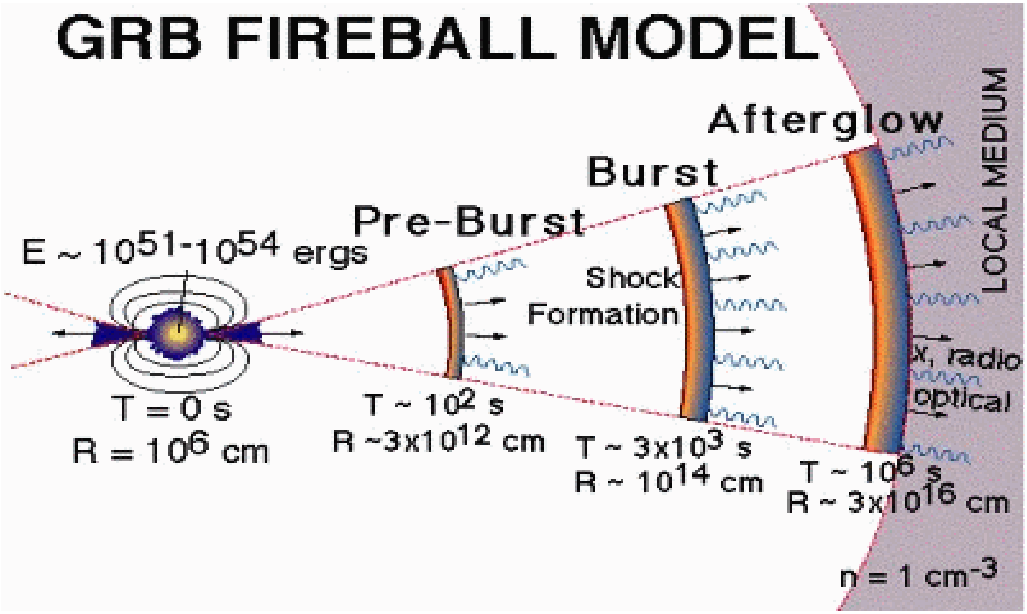
$$(\alpha - \beta)E_0 \leq E$$

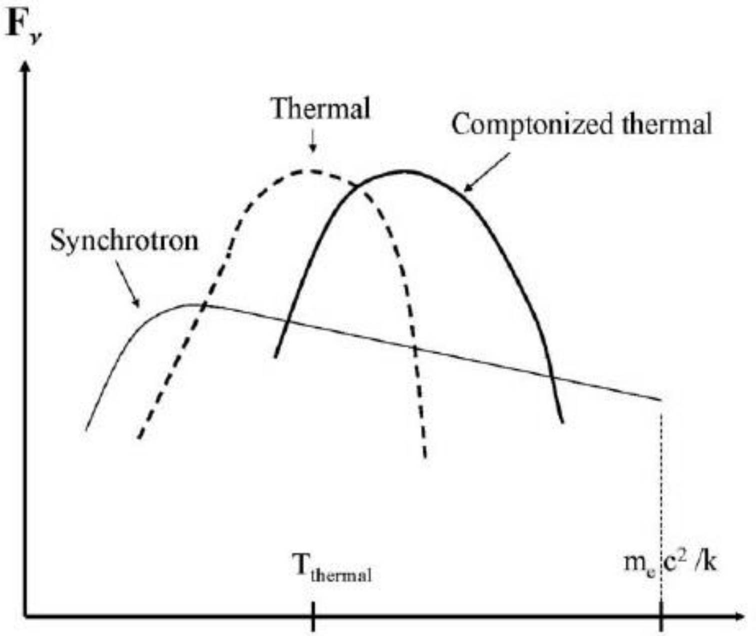


➢ $E_p = E_0 \times (2 + \alpha)$ = peak energy of the $\nu F \nu$ spectrum

➢ Ep is a fundamental parameter in GRB emission models

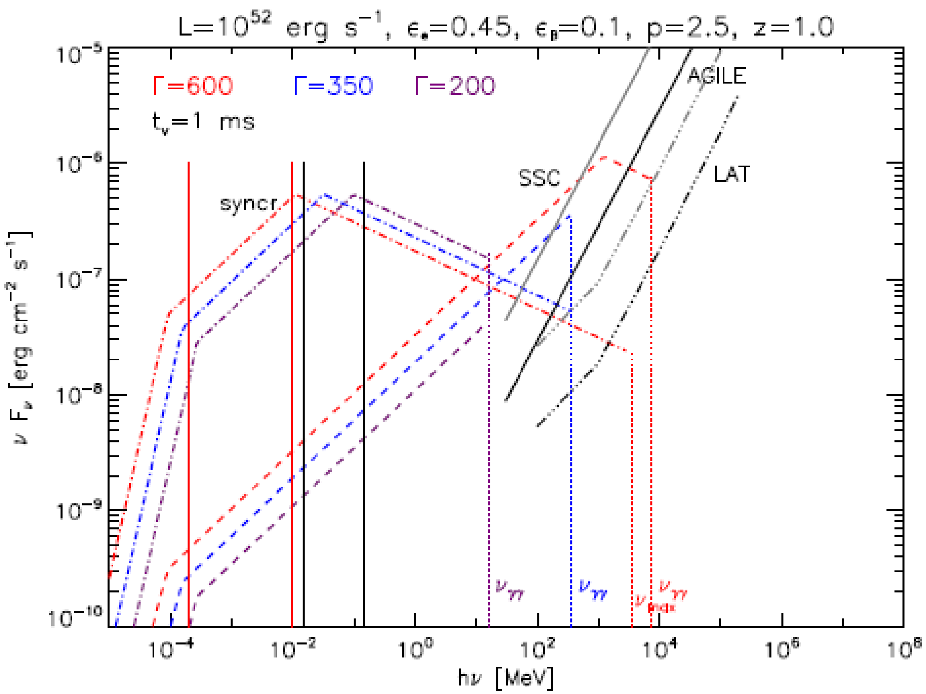
❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy / Poynting flux dominated fireballs, …



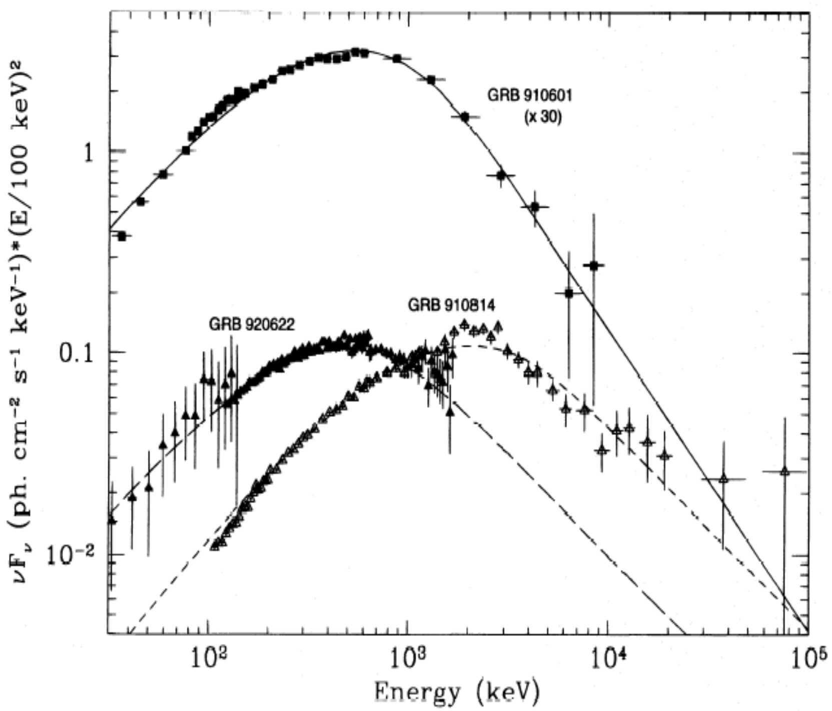


➢ Ep is a fundamental parameter in GRB emission models

➢ 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

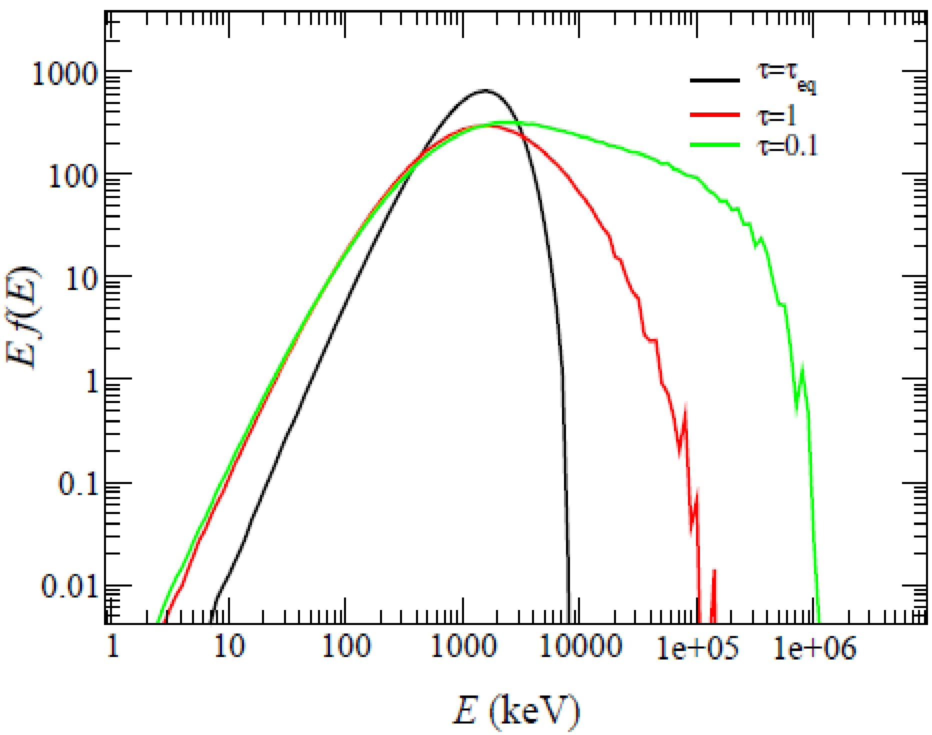


Galli & Guetta 2007

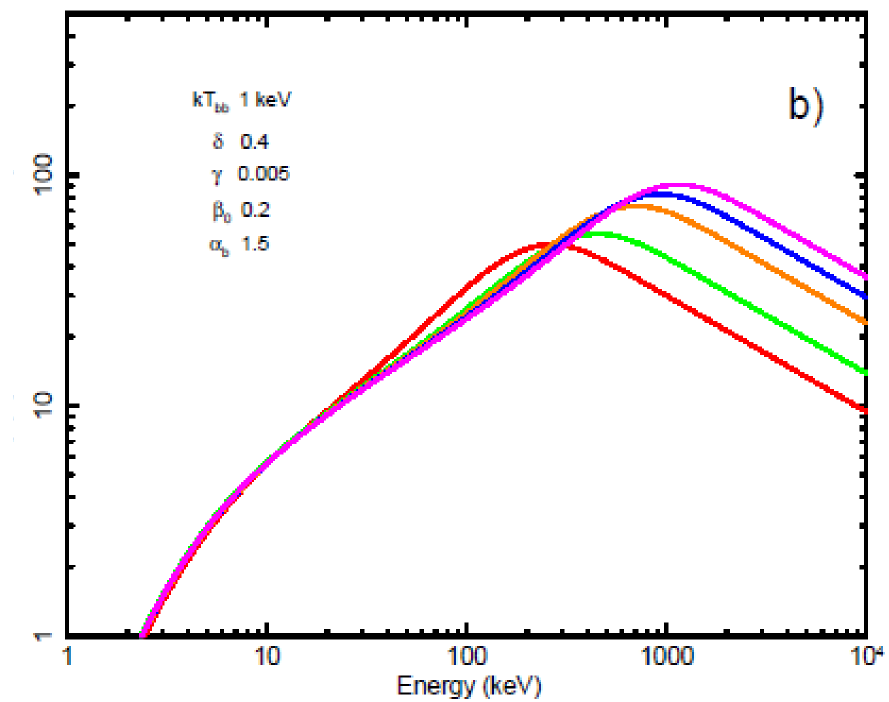


Tavani, ApJ, 1995

➢ 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

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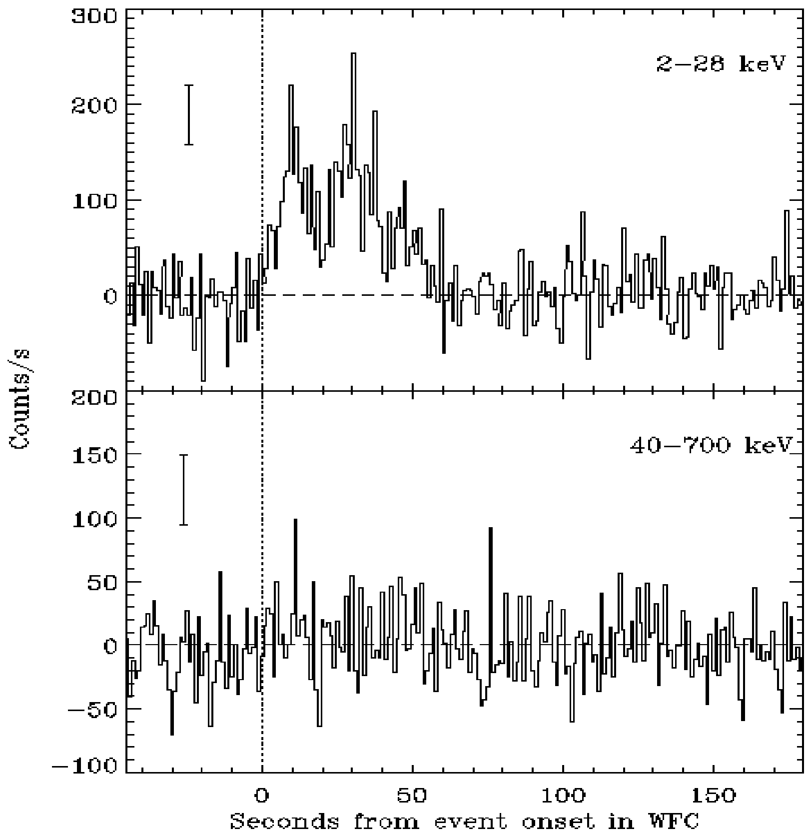
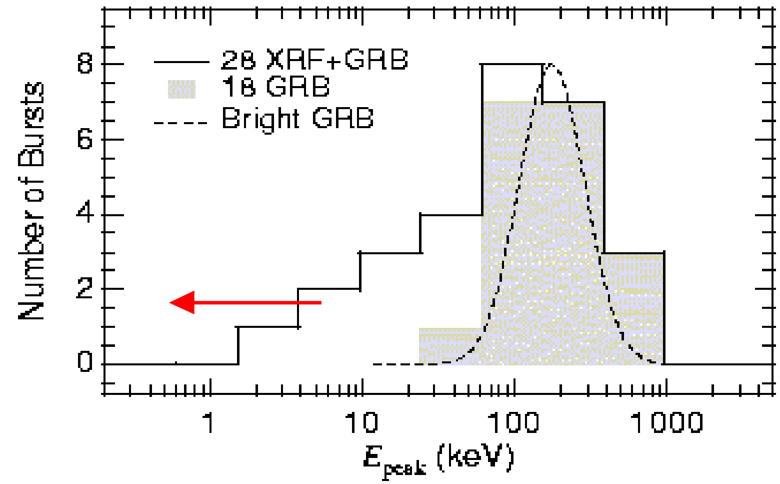
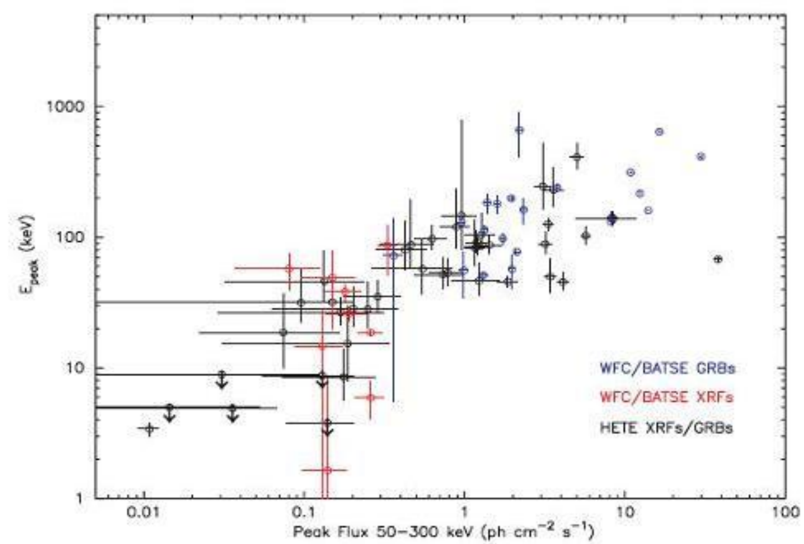
- CGRO/BATSE (25-2000 keV): Ep values distibuted around 200 keV
- BeppoSAX (2-700 keV) and HETE-2 (2-400 keV) XRFs measurements show that the E_p distribution is broader and extending towards low energy than inferred from BATSE



Amati et al., A&A, 2004





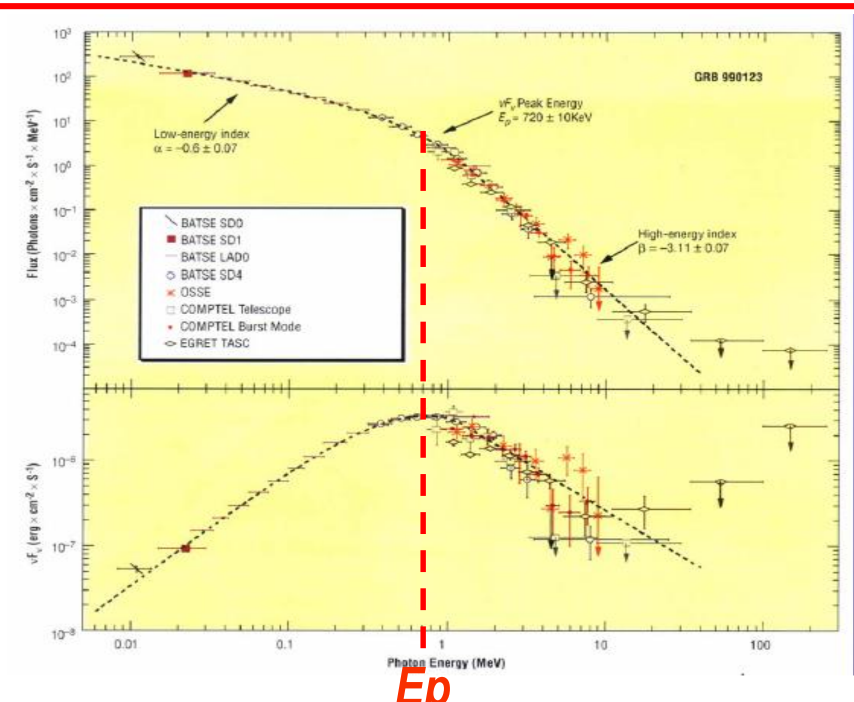
Kippen et al 2011; Sakamoto et al. 2005.

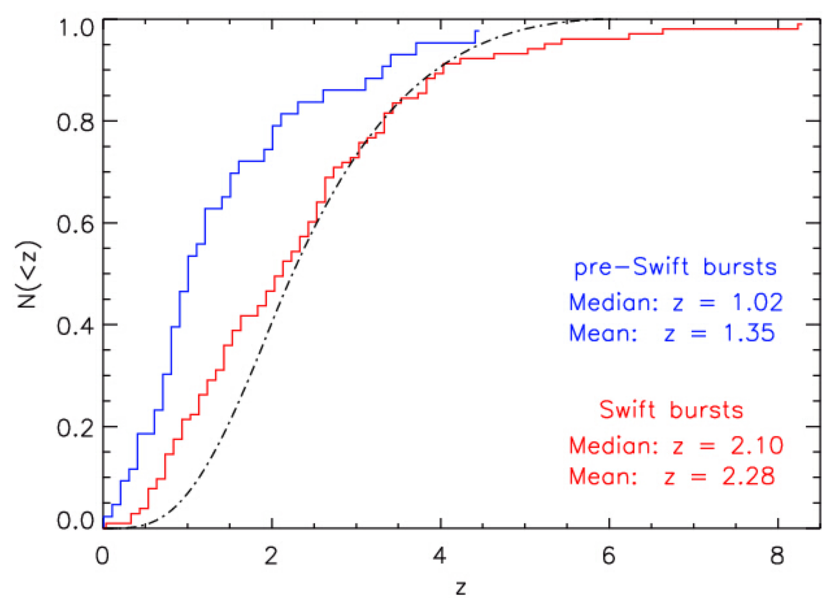
The Ep,i – Eiso correlation

- GRB spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy
- $E_p = E_0 \times (2 + \alpha)$ = observed peak energy of the $\nu F \nu$ spectrum
- **measured spectrum + measured redshift -> intrinsic peak enery and radiated energy**

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

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

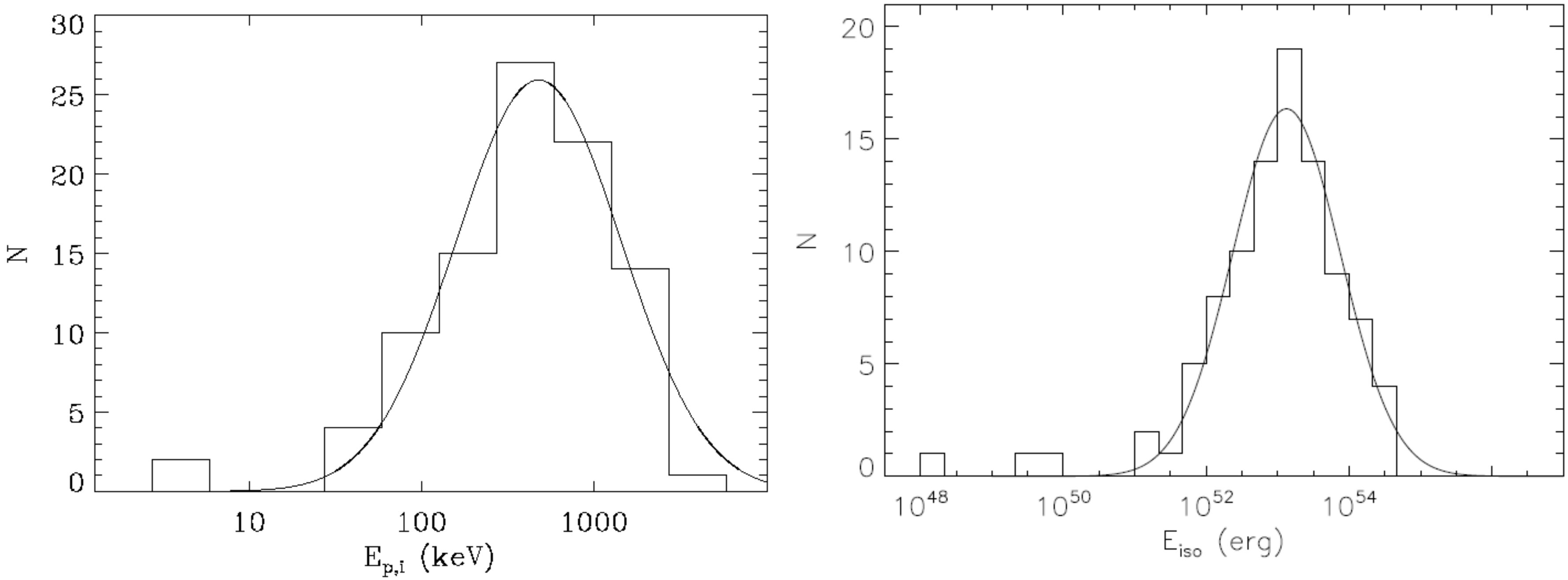




Jakobsson (2009)

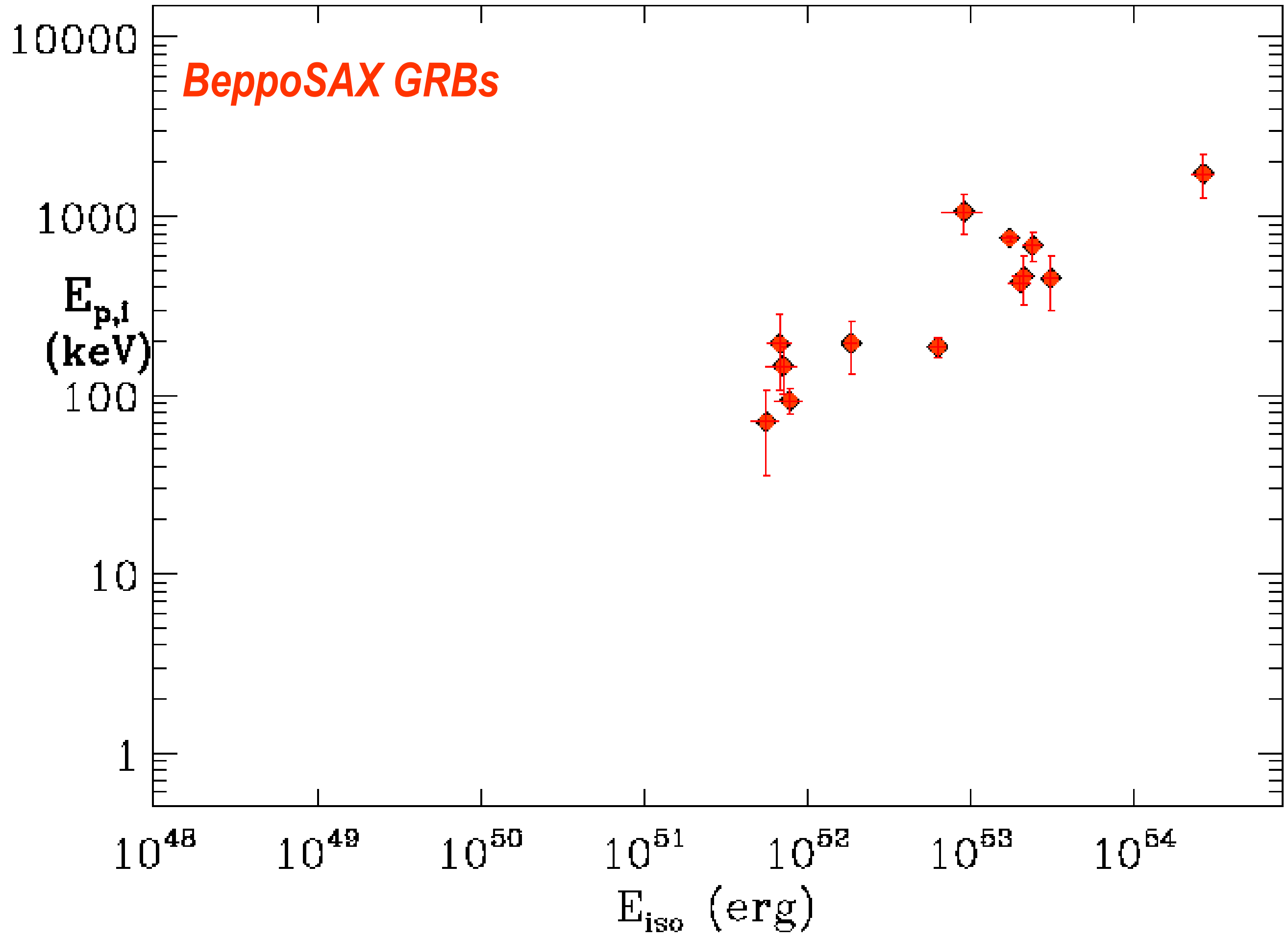
➢ **~300 GRBs with measured redshift, about 50% have measured spectra (Ep)**

➢ both Ep,i and Eiso span several orders of magnitude and a distribution which can be described by a Gaussian plus a low – energy tail (“intrinsic” XRFs and sub-energetic events)



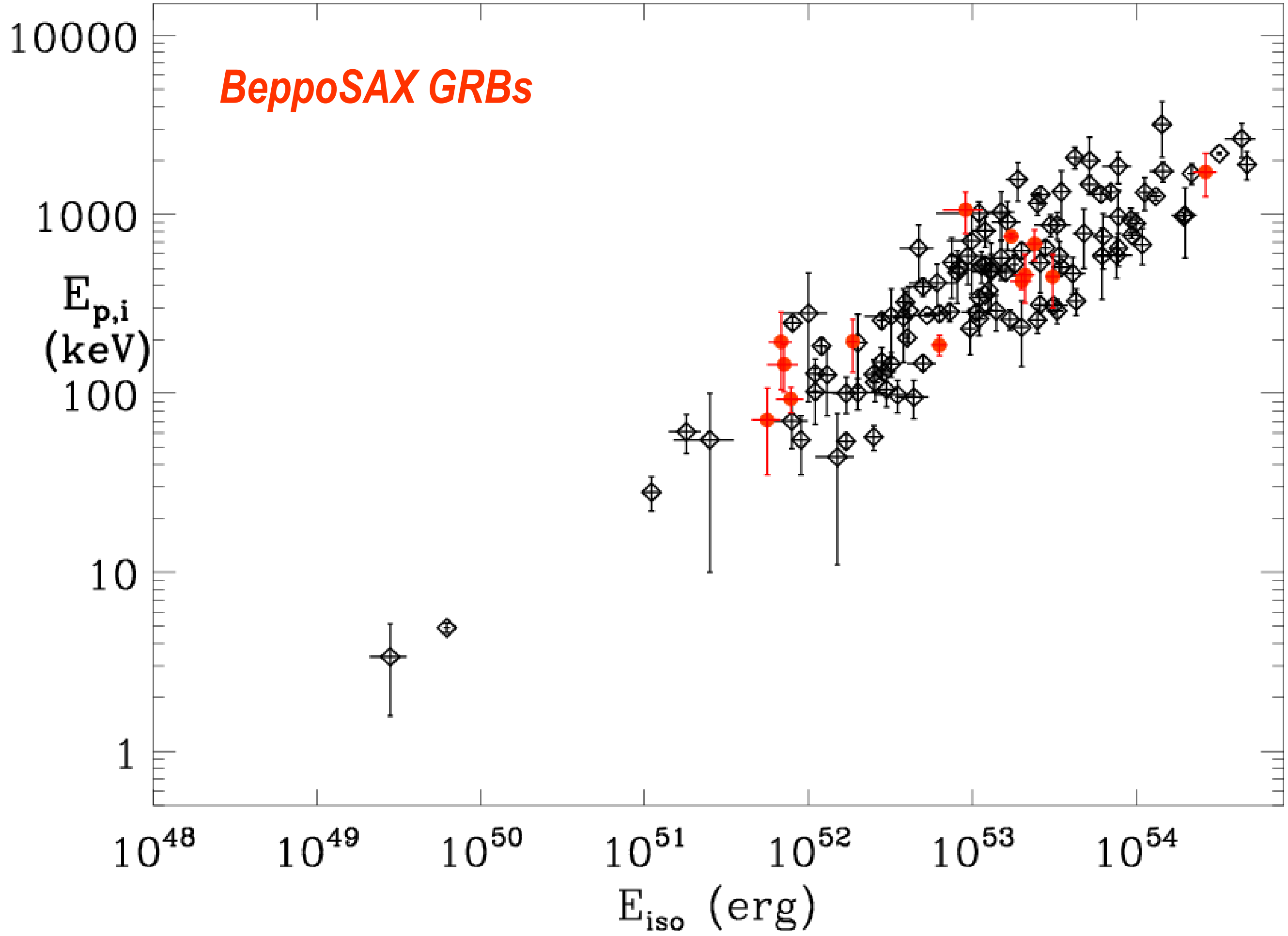
95 GRBs, sample of Amati, Frontera & Guidorzi, A&A (2009)

➢ 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



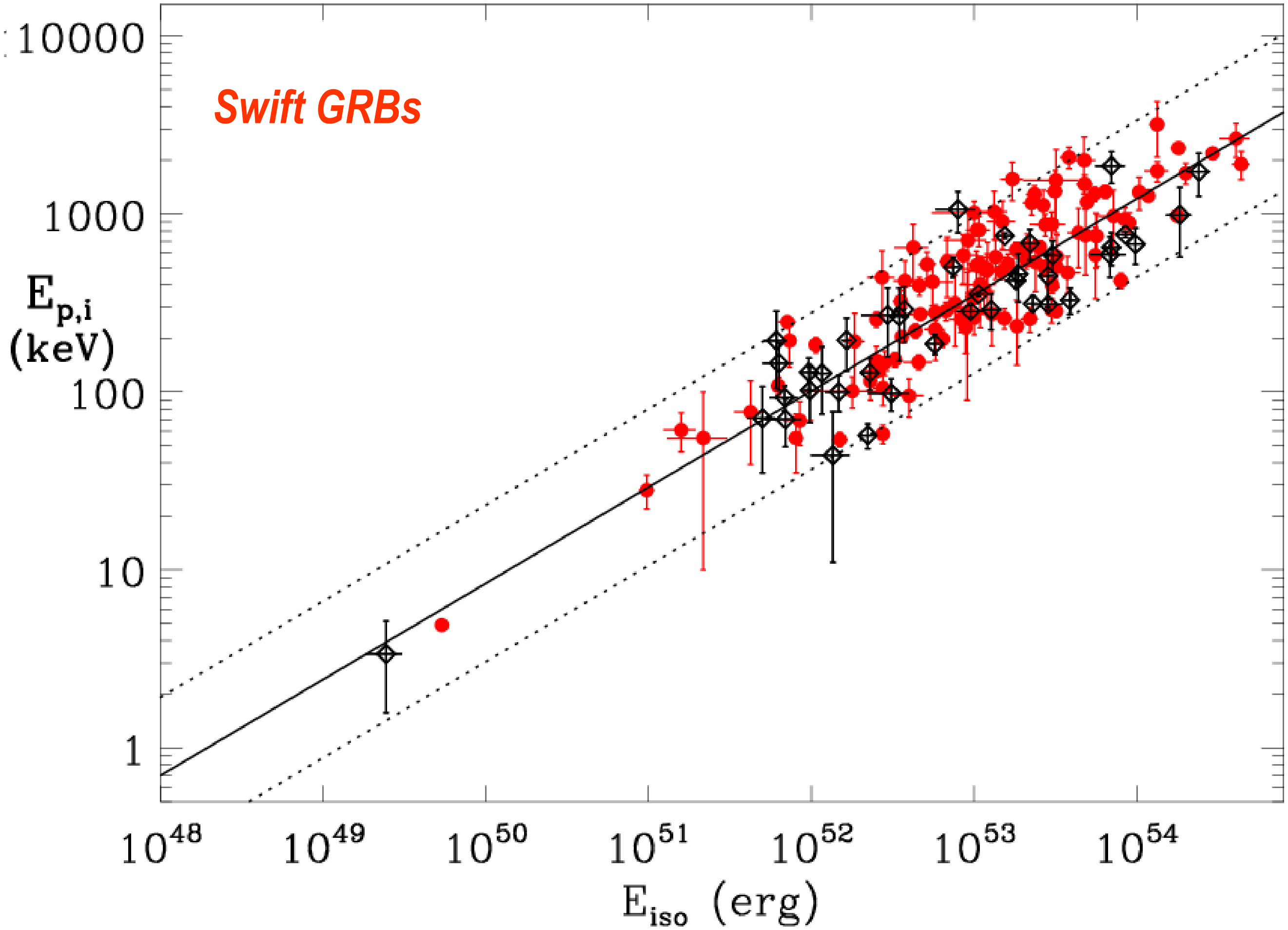
➢ Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities

131 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 (e.g., HETE-2, Konus-WIND, Swift/BAT, Fermi/GBM)

152 long GRBs as of Sept. 2012

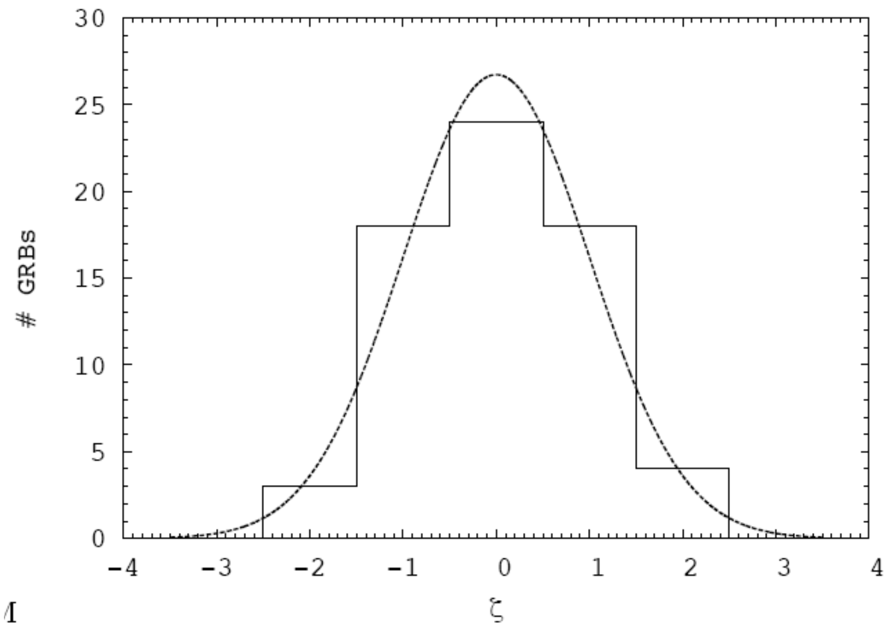


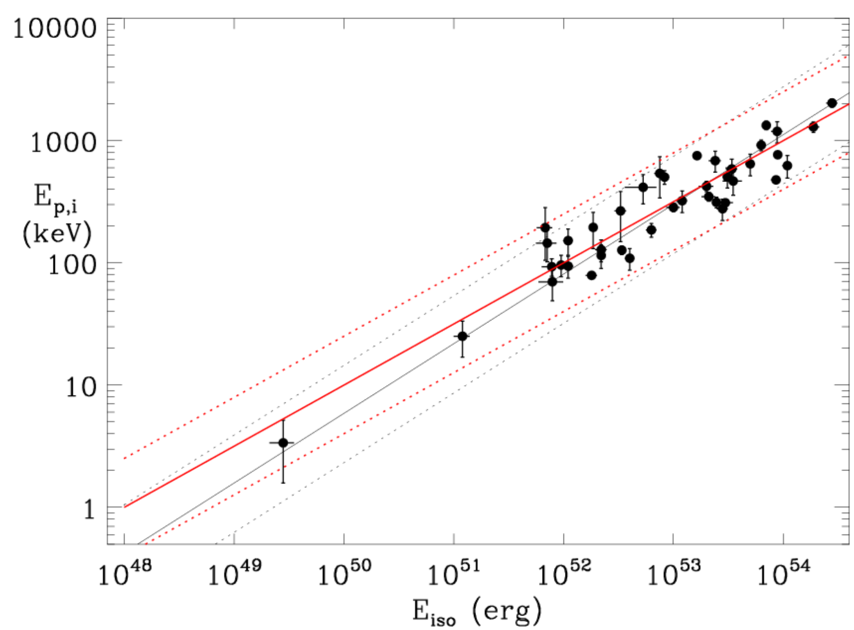
➢ strong correlation but significant dispersion of the data around the best-fit power-law; the distribution of the residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

➢ the "extra-Poissonian 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

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

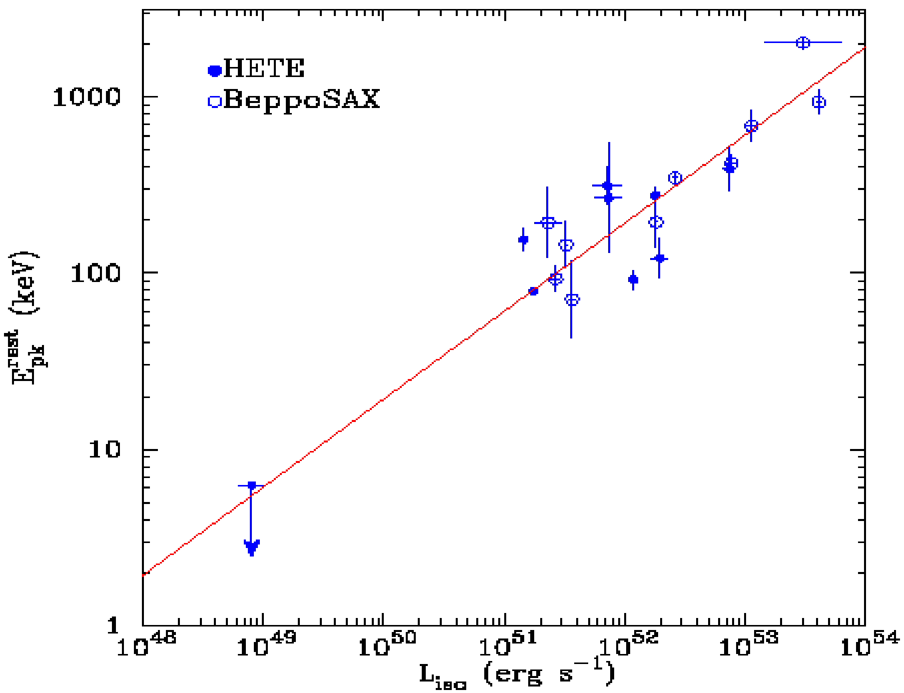
➢ with this method Amati et al. (2008, 2009) found an extrinsic scatter σ_{int}(logEp,i) ~ 0.2 and index and normalization ~0.5 and ~100, respectively

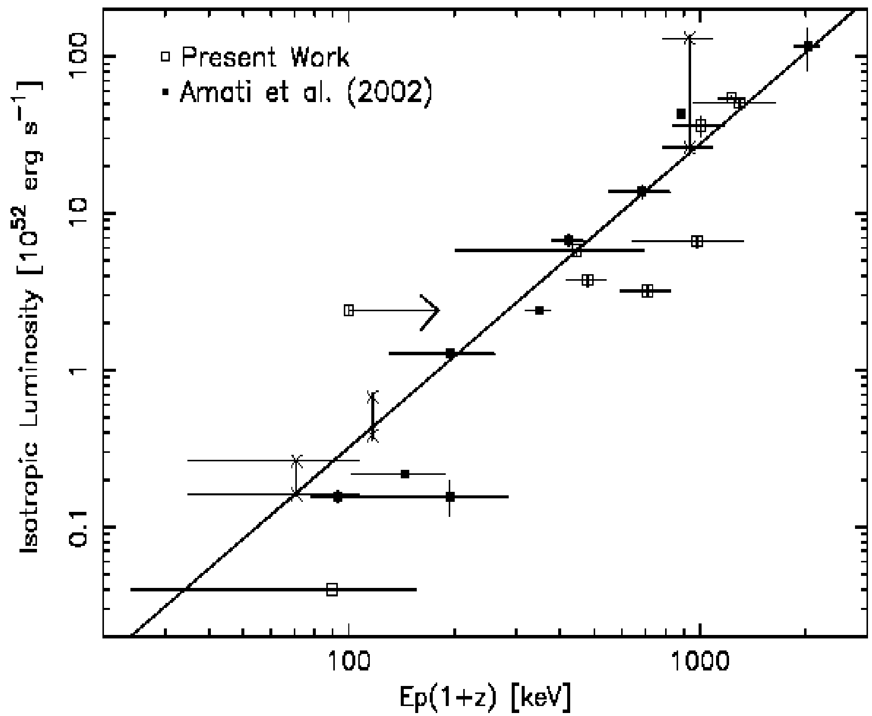




Other Ep,i – Intensity correlations

- 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**





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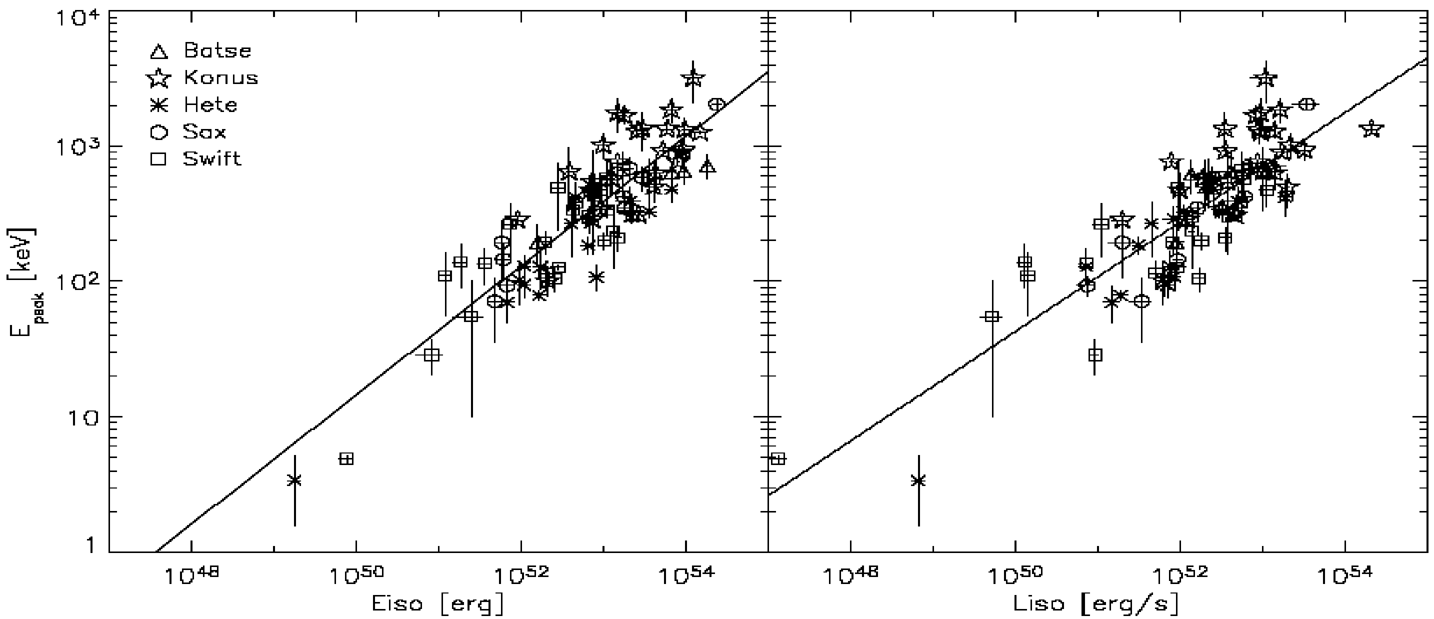


Nava et al. 2009

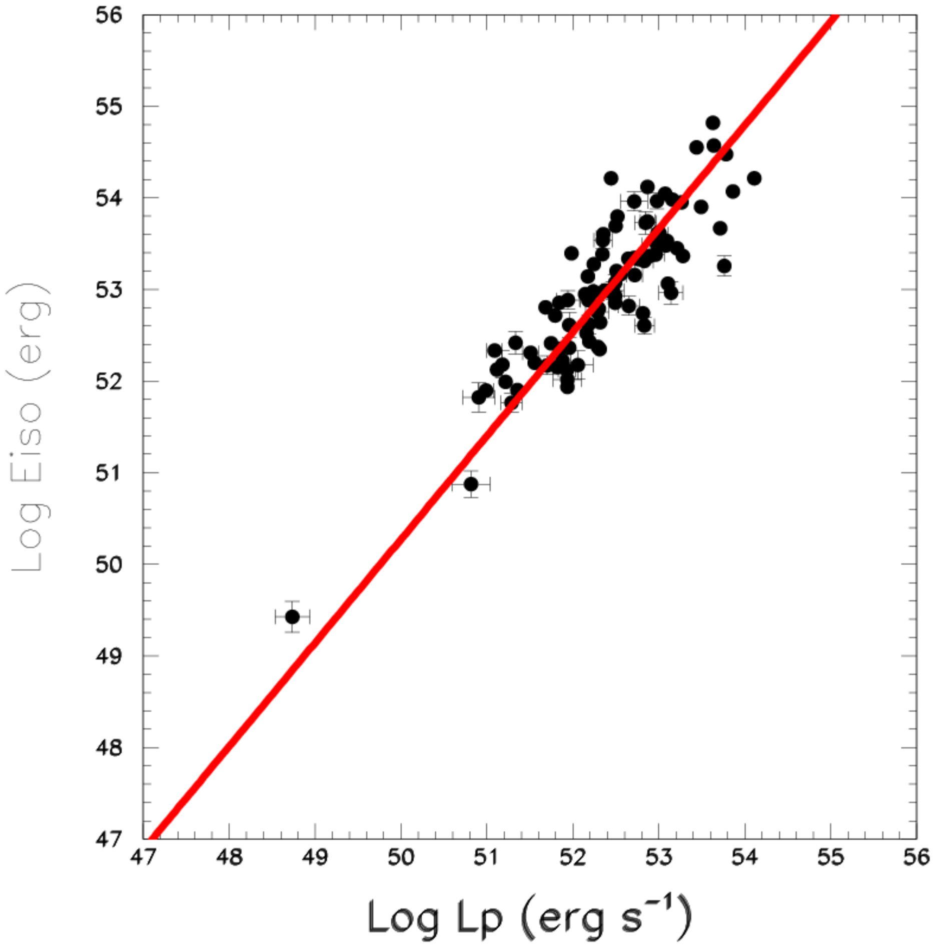


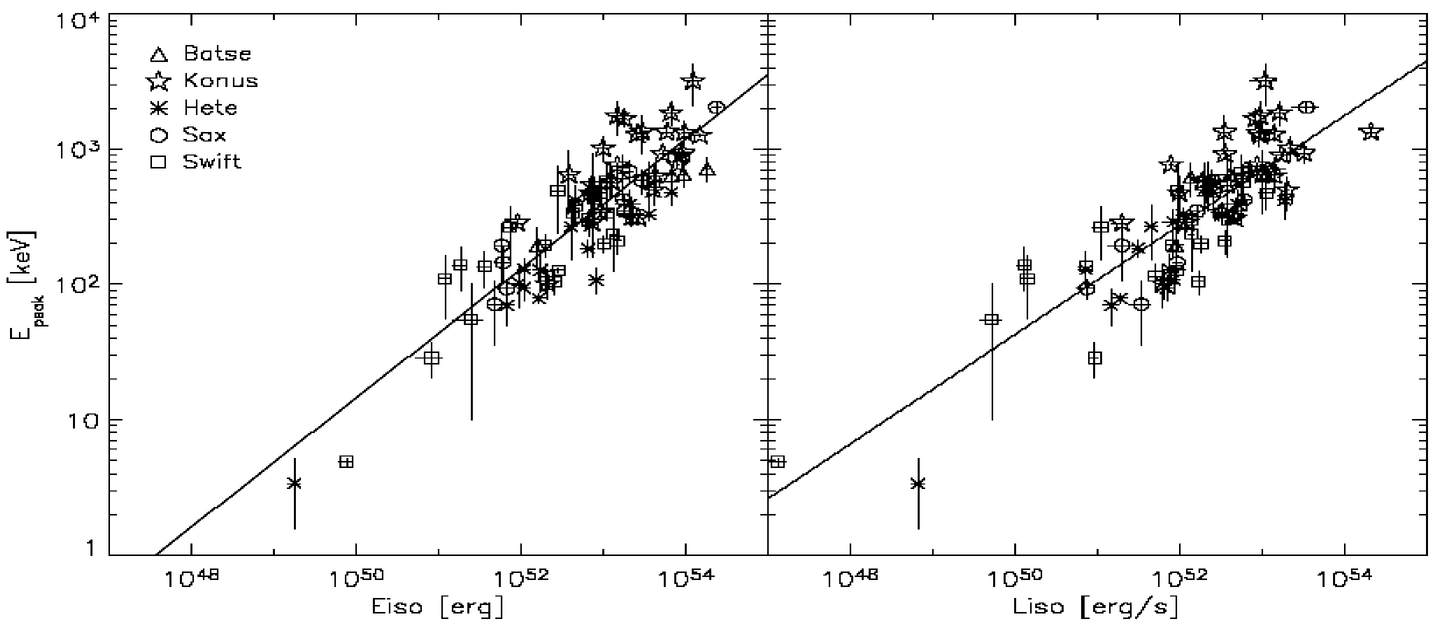
Fig. 3.— The observed correlation between $E_{\gamma,iso}$ and $L_{p,\gamma}$ and for 96 GRBs with known redshift compiled by Yonetoku et al. (2010) The best fit power-law correlation (straight line) has a power-law index 1.13 .

Dado & Dar 2012

➢ 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)

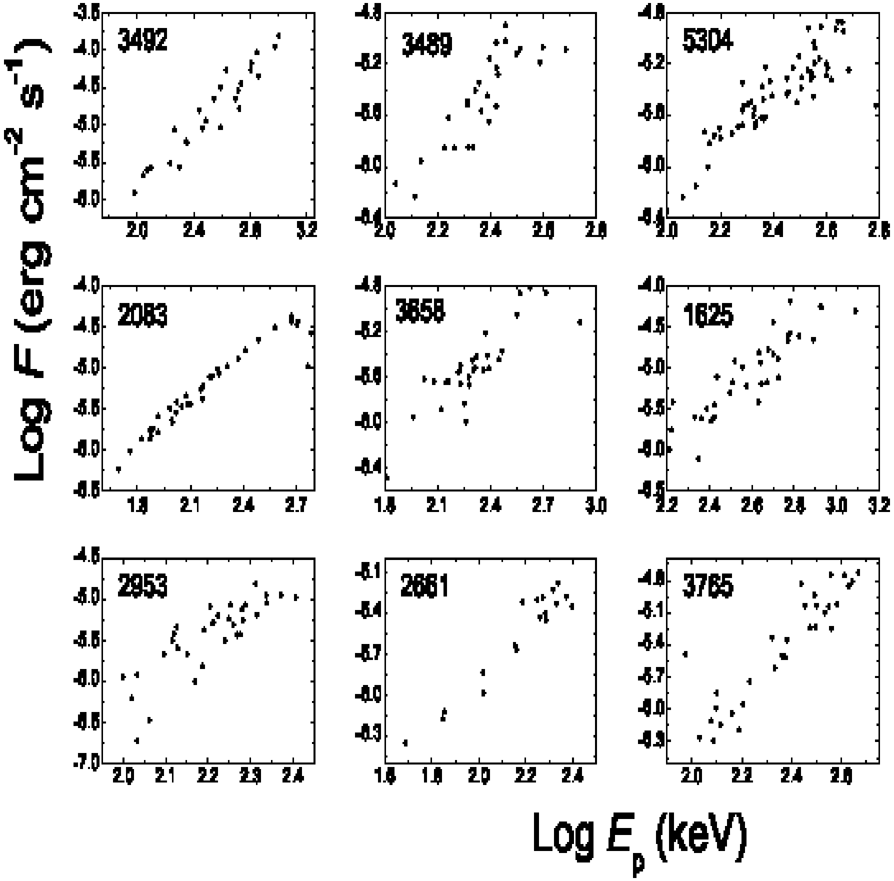
➢ this is expected because **Liso and Lpeak,iso are strongly correlated with Eiso**

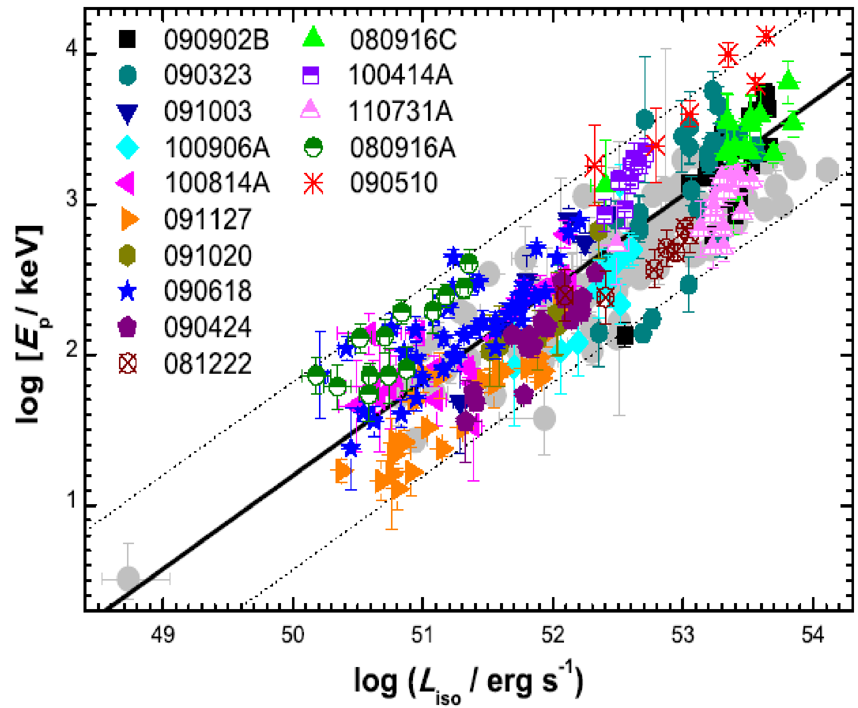
➢ w/r to Eiso, **Lp,iso is subject to more uncertainties** (e.g., light curves peak at different times in different energy bands; spectral parameters at peak difficult to estimate; which peak time scale ?)



Nava et al. 2009

➢ the Ep,i– Liso 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**

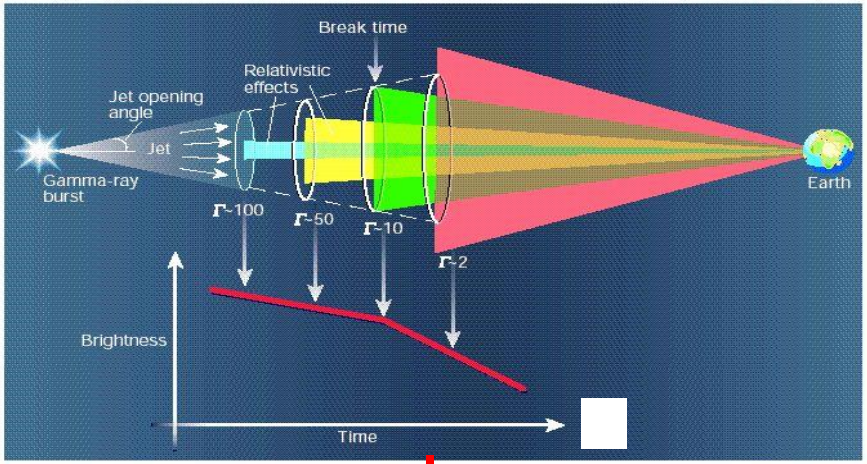




BATSE (Liang et al., ApJ, 2004)

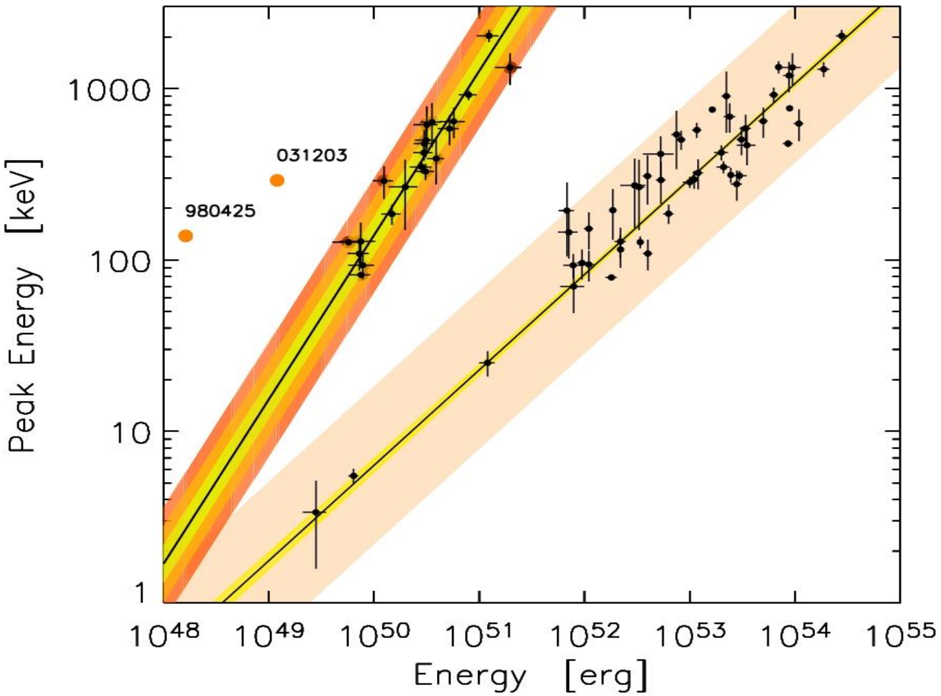
Fermi (e.g., Li et al. , ApJ, 2012)

❑ 2004: evidence that by substituting Eiso with the collimation corrected energy Eγ the logarithmic dispersion of the correlation decreases significantly and the sloep becomes steeper (Ghirlanda et al., Dai et al, and many)



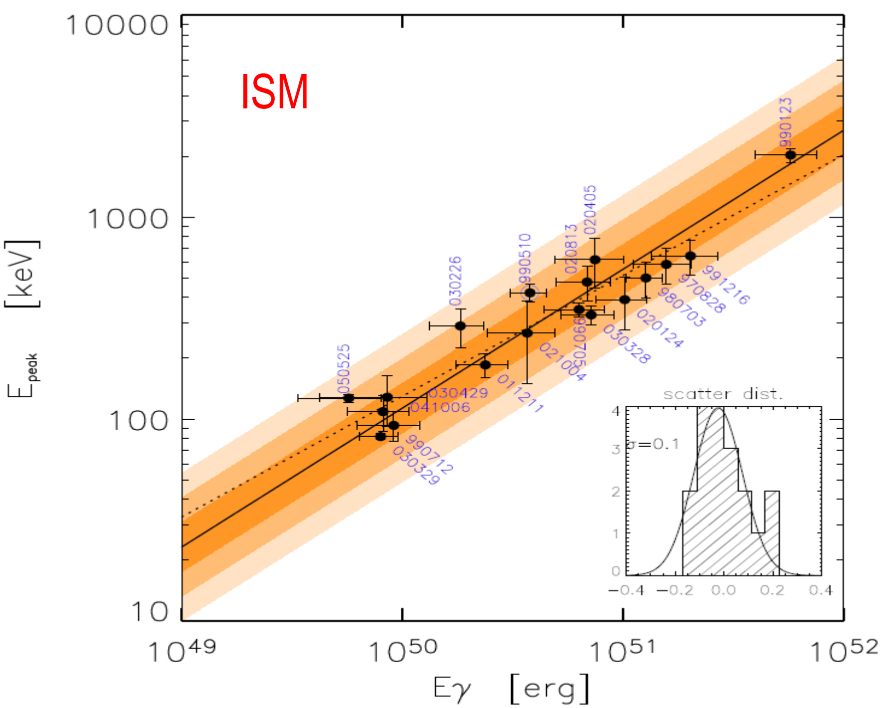
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

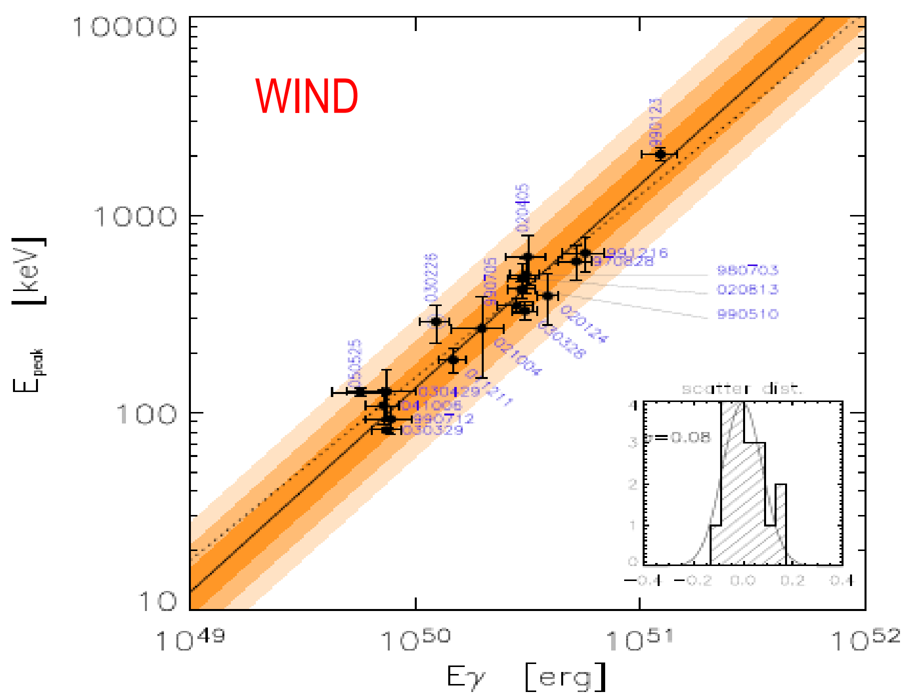
$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$



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

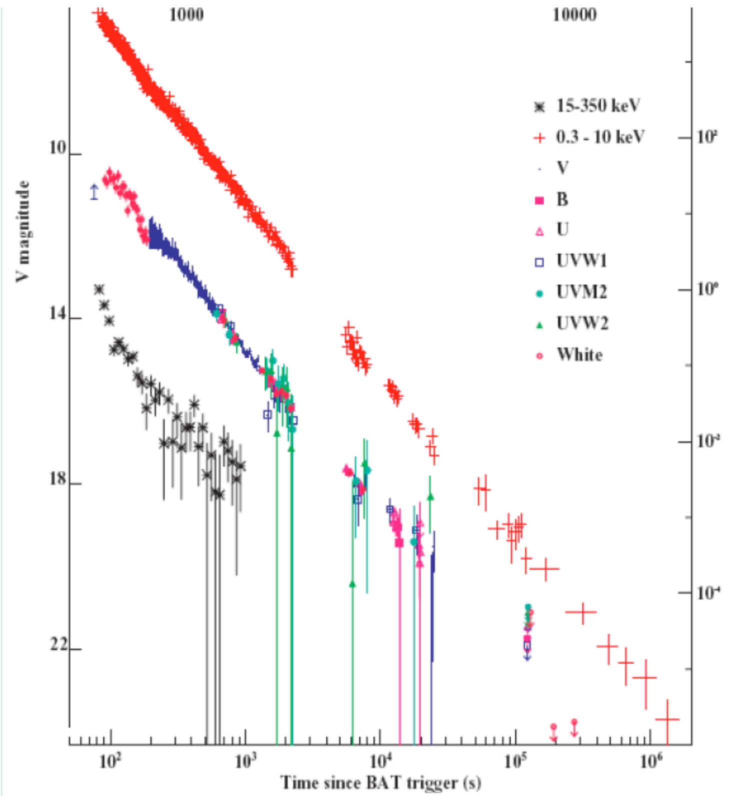
➢ **addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, and reduces substantially the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)

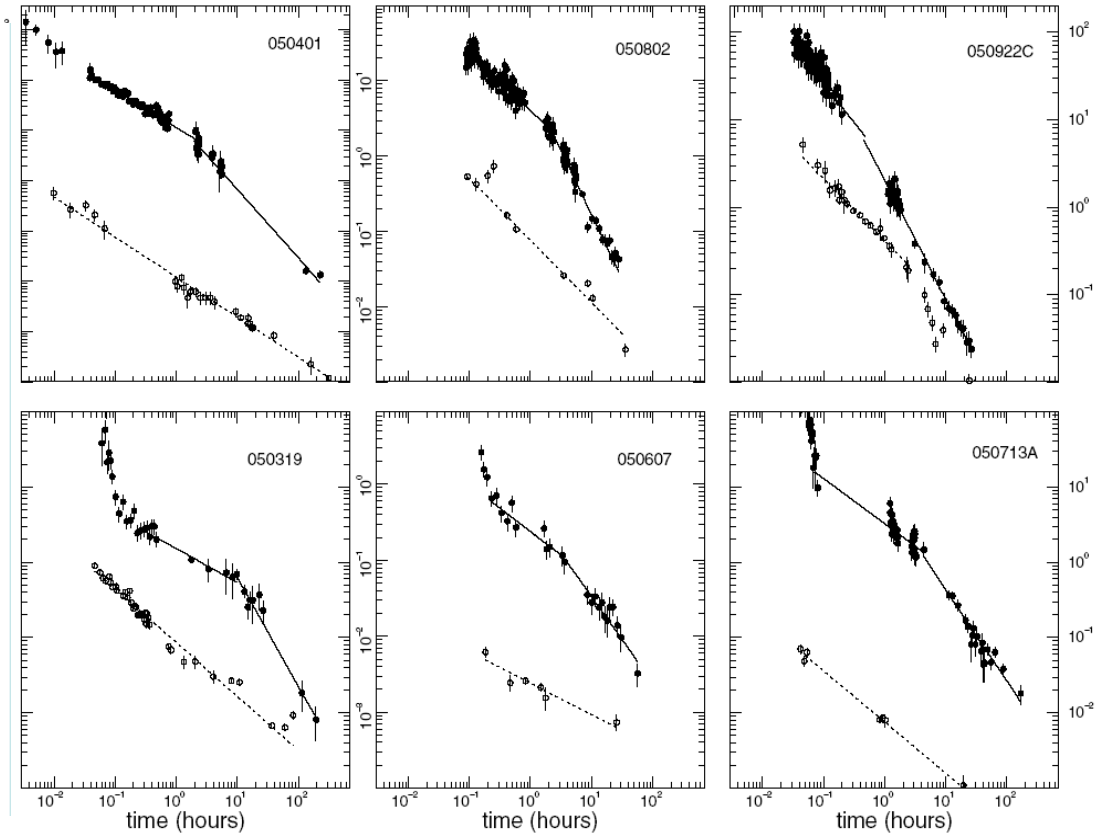




Nava et al.. , A&A, 2005: ISM (left) and WIND (right)

- 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 ?

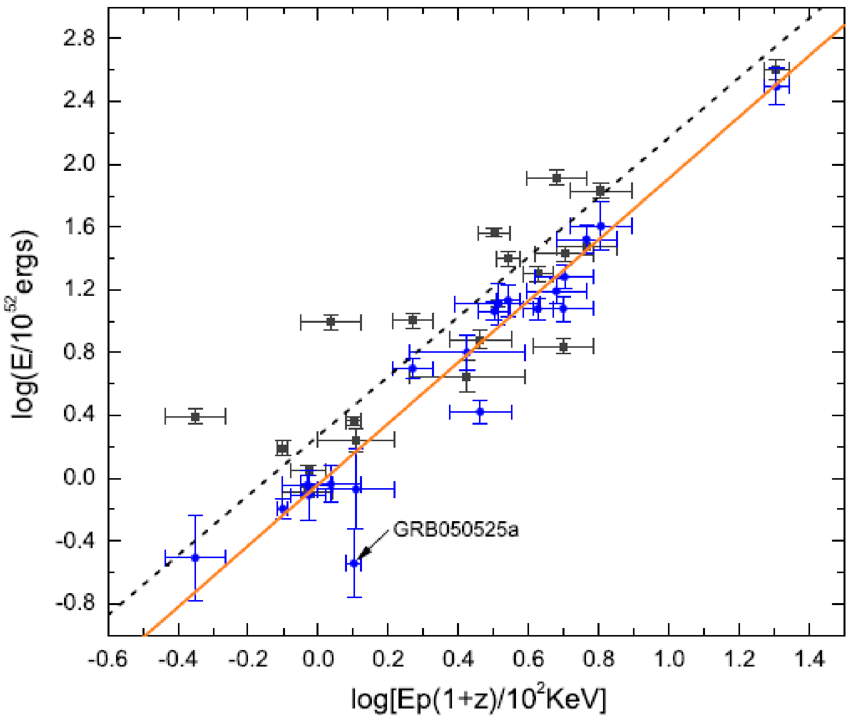




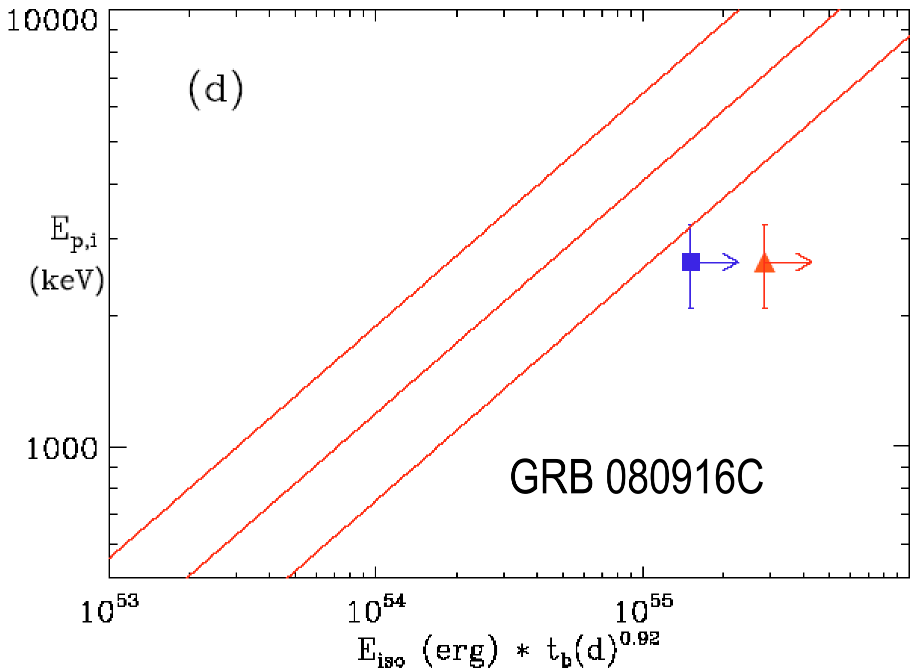
- Liang & Zhang (2005) and Xu (2005) performed a multi-variable correlation analysis between various observables of prompt and afterglow, founding a tight correlation between Epi, Eiso and tb

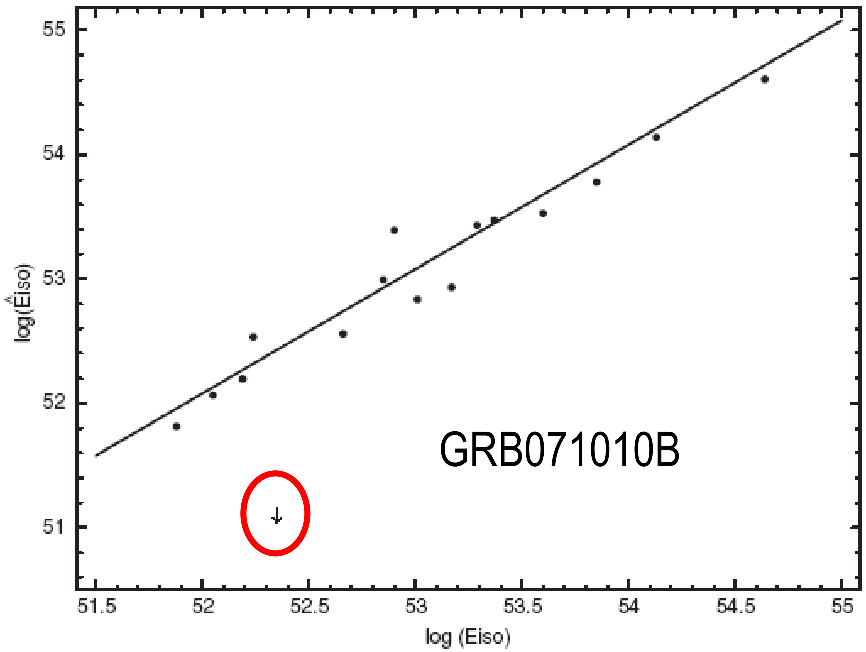
- with respect to Ep,i – Eg correlation it has the advantage of being model independent, but it is somewhat more dispersed

$$\hat{E}_{\gamma,\mathrm{iso},52} = (0.90 \pm 0.18) \times \left(\frac{E'_{\mathrm{p}}}{100\ \mathrm{keV}}\right)^{1.90\pm0.13} \times \left(\frac{t'_{\mathrm{b}}}{1\ \mathrm{day}}\right)^{-0.94\pm0.19},$$



➢ growing number of outliers to the Ep-Eiso-tb correlation



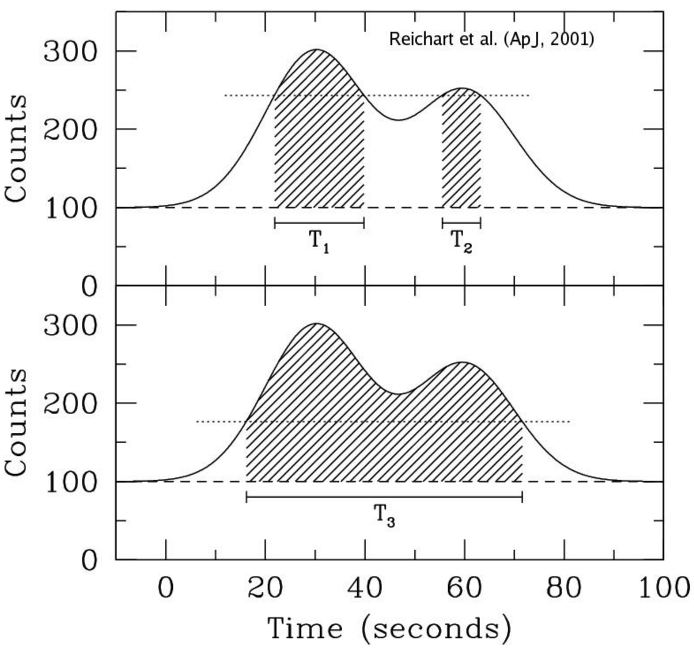


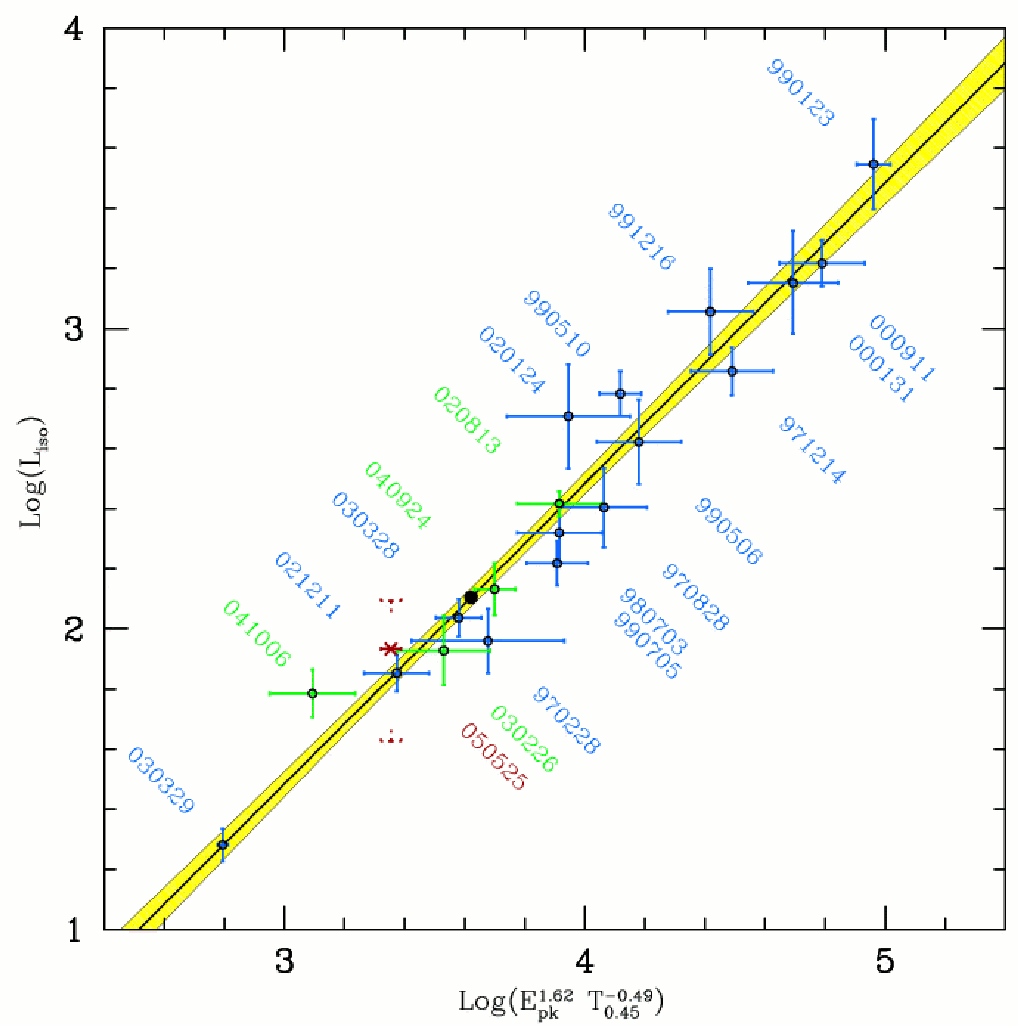
Amati, Frontera, Guidorzi 2009

Urata et al. 2009

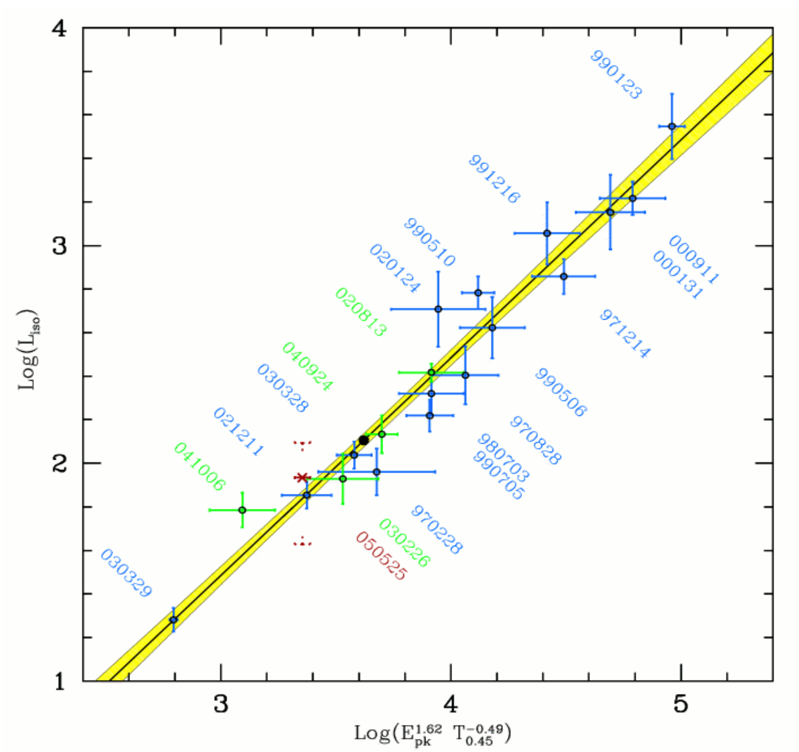
❑ A tight correlation between Ep,i, Lpeak,iso and time scale $T_{0.45}$ was also claimed, based on still small number of events and proposed for standardizing GRBs (Firmani et al. 2006 and others)

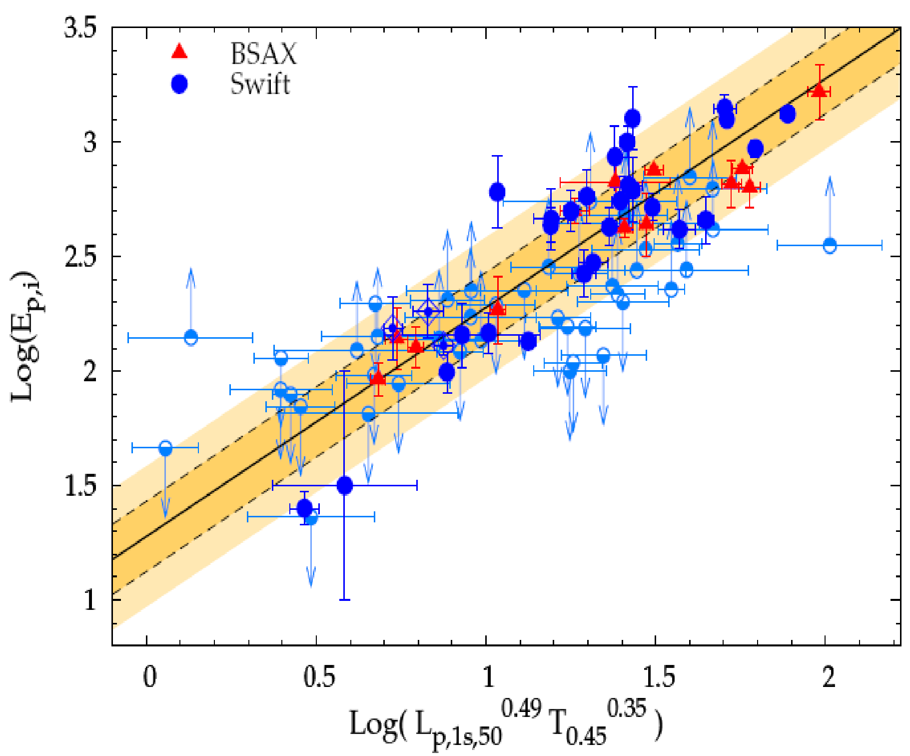
$$L_{\rm iso} \propto E_{\rm pk}^{1.62} T_{0.45}^{-0.49}$$



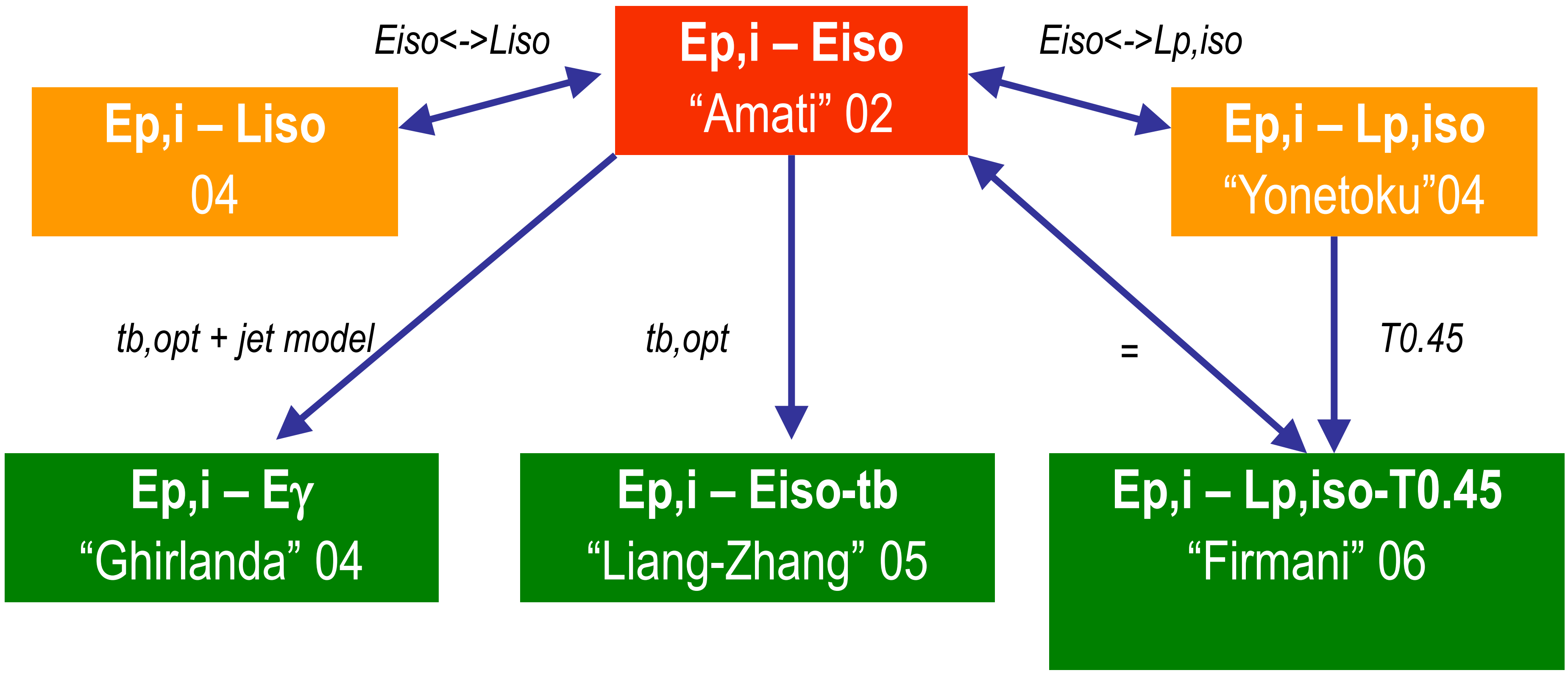


❑ … but Rossi et al. 2008 and Schaefer et al. 2008 , based on BeppoSAX and Swift GRBs, showed that the dispersion of the Lp-Ep-$T_{0.45}$ correlation is significantly higher than thought before and that the Ep,i-Lp,iso-T0.45 correlation my be equivalent to the Ep,i-Eiso correlation





❑ Ep,i - intensity correlations



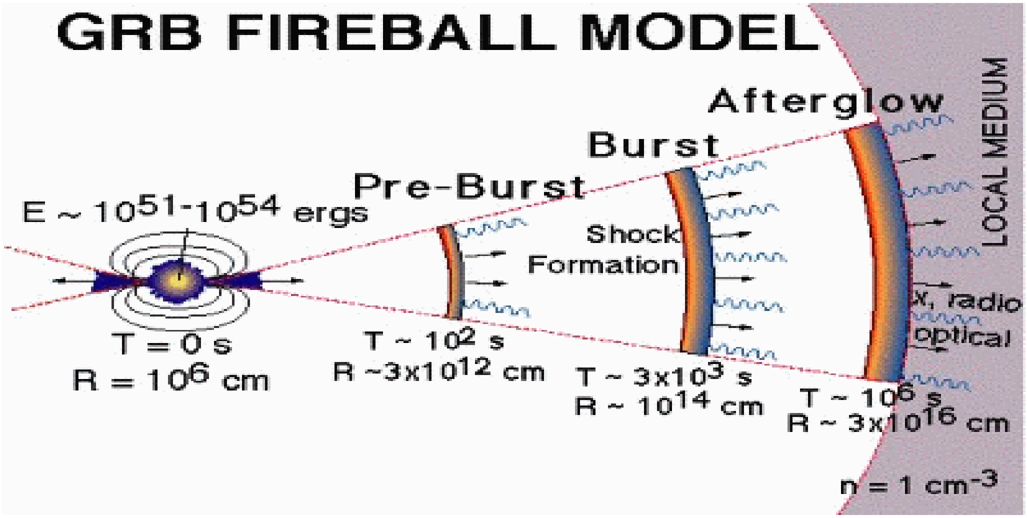
Implications and uses of the Ep,i – intensity correlation

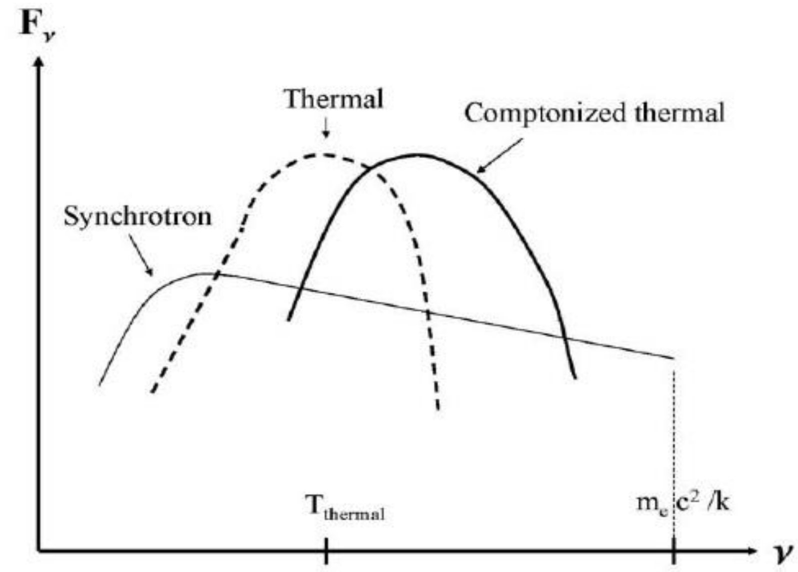
➢ prompt emission physics

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

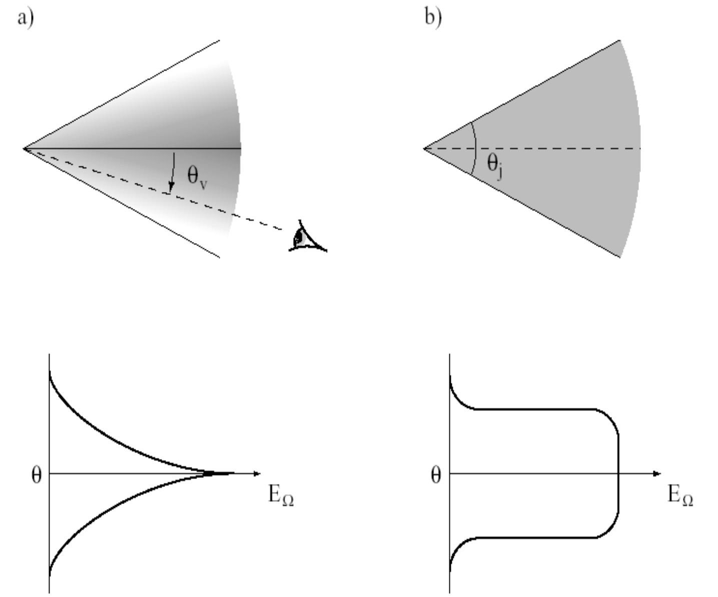
- e.g., $E_p \propto R_0^{-1/2} t_j^{-1/4} E_{\rm iso}^{1/2}$ in scenarios in whch for comptonized thermal emission from the photosphere dominates (e.g. Rees & Meszaros 2005, Thomson et al. 2006)

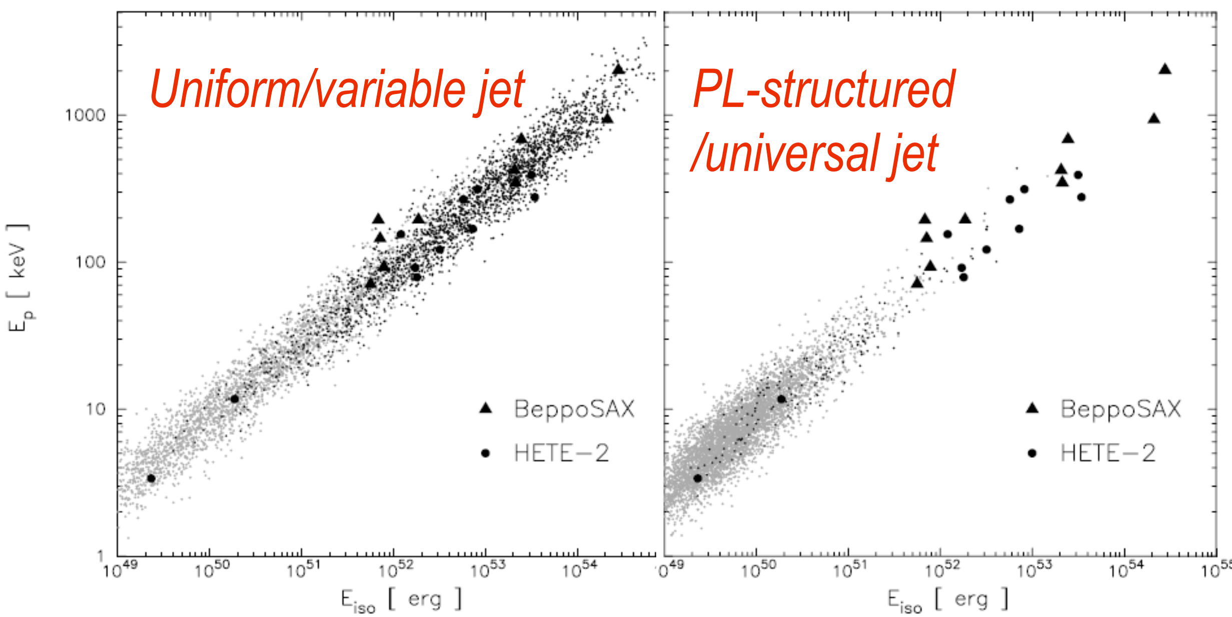




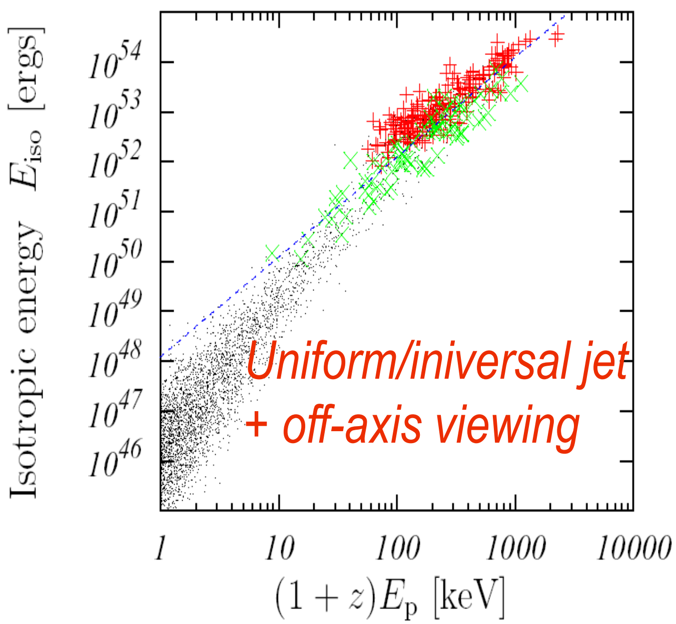
➢ implications and uses: jet structure and viewing angle effects

- ❑ jet geometry and structure and XRF-GRB unification models (e.g., Lamb et al. 2004)
- ❑ viewing angle effects: $\delta=[\gamma(1 - \beta\cos(\theta v - \Delta\theta))]^{-1}$, $\Delta Ep \propto \delta$, $\Delta Eiso \propto \delta^{(1+\alpha)}$ (e.g, Yamazaki et al.)



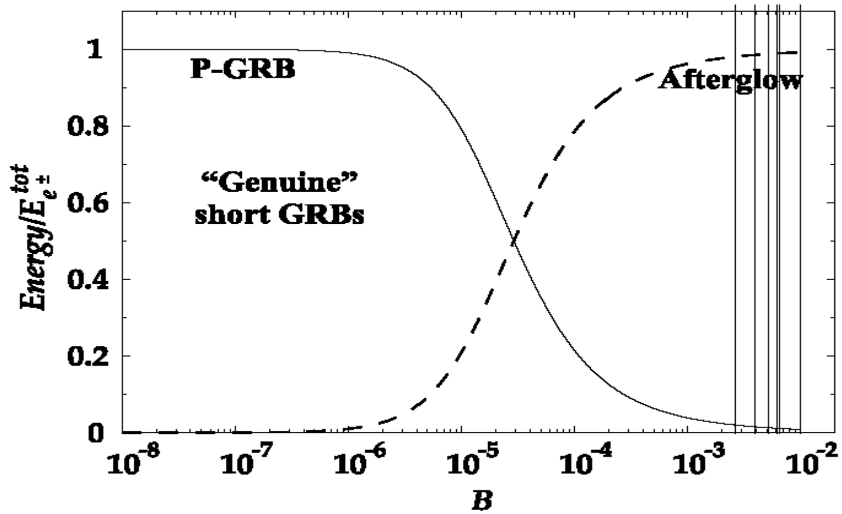


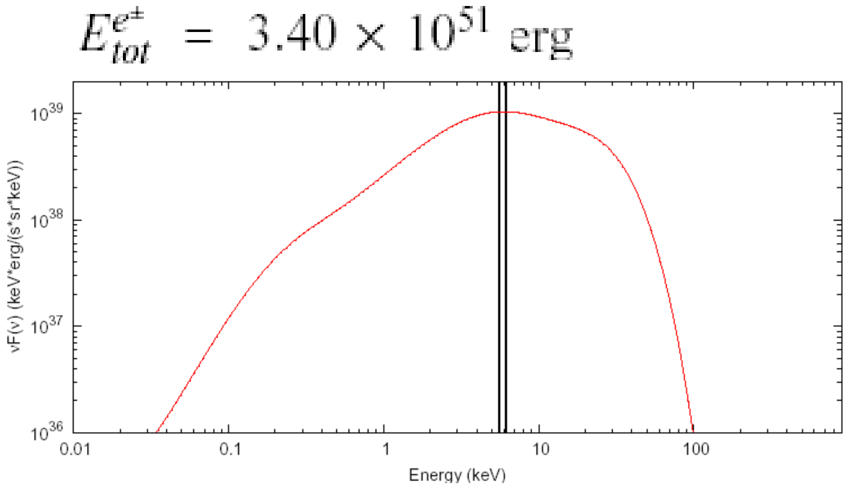
Lamb et al. 2005

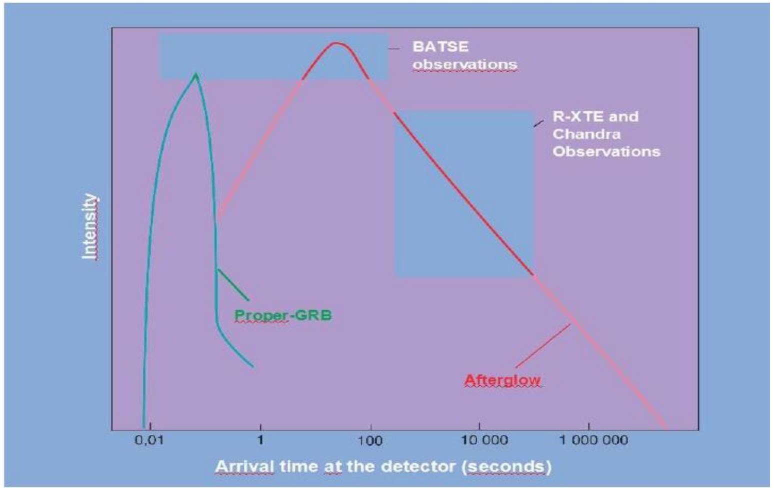


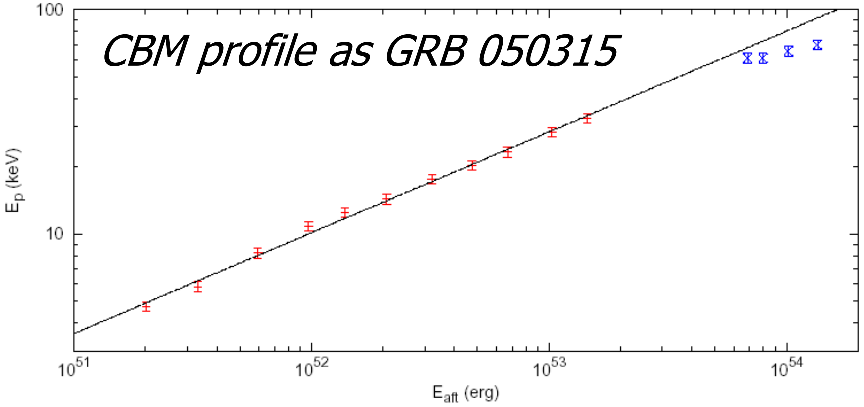
Yamazaki et al. 2004

- Ep,i – Eiso correlation in alternative scenarios, e.g. the "fireshell model" by Ruffini et al.: by assuming CBM profile from a real GRB and varying Etot, the correlation is obtained, with a slope of 0.45+/+0.01 (consistent with obs.) (Guida et al. 2008)



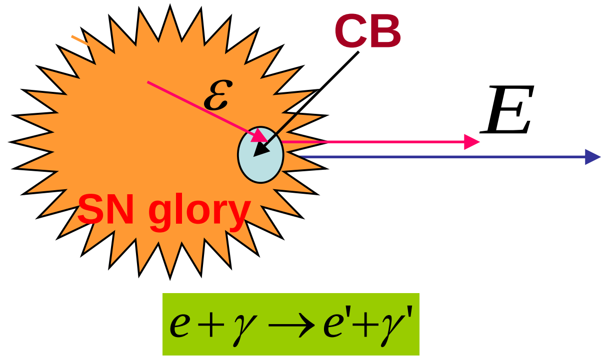






- Ep,i – Eiso correlation also predicted in the "cannon-ball model" by Dar et al. with a specific functional shape

$$E \approx \gamma\delta\varepsilon(1+\cos\vartheta_i)/(1+z)$$



$$\delta \approx 2\gamma/(1+\gamma^2\vartheta^2)$$

$$(1+z)E_p \propto \gamma\delta$$

$$E_{iso}^{\gamma} \propto \delta^3$$

$$L_p \propto \delta^4/(1+z)$$

For a single CB :

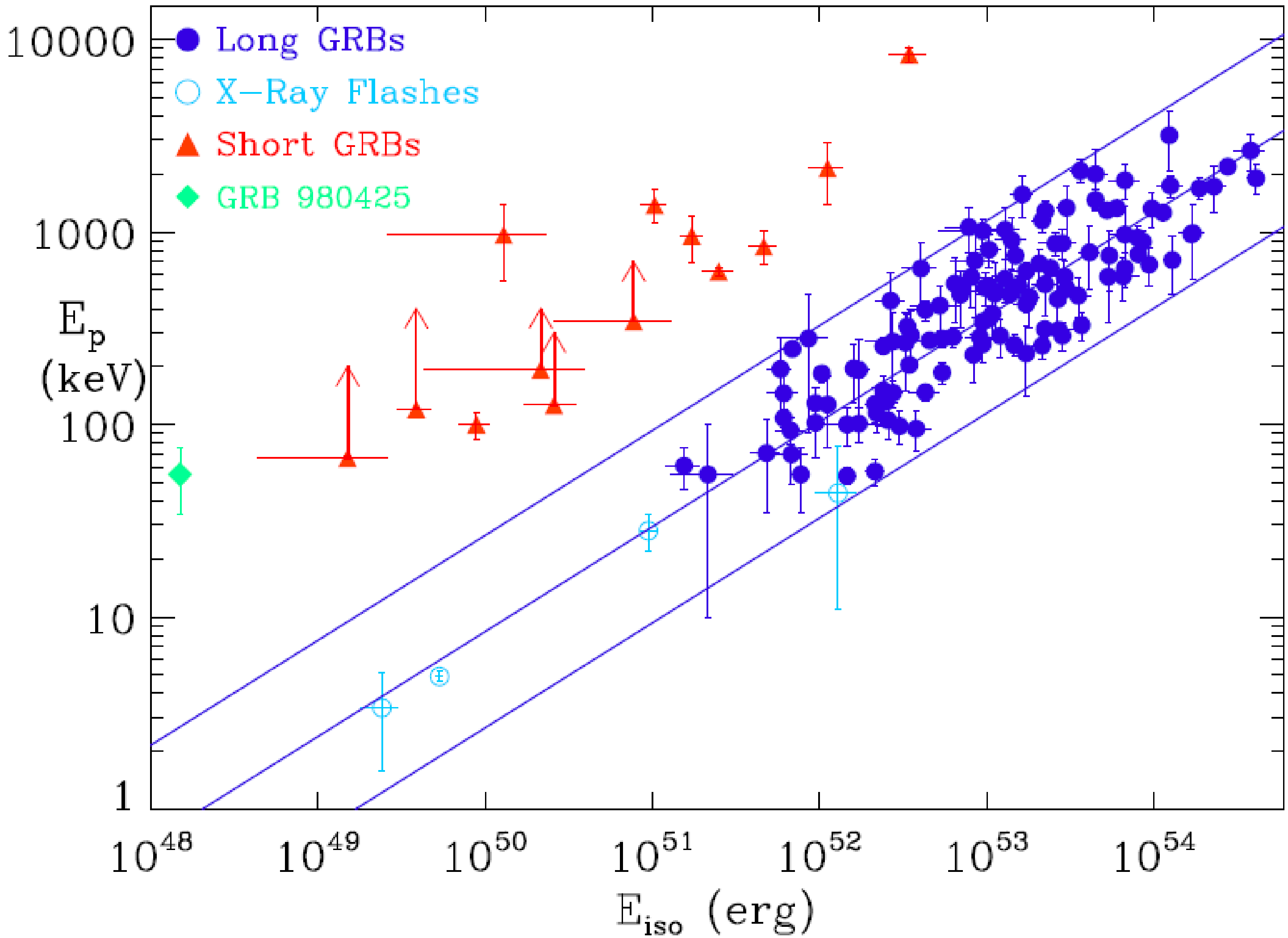
$$\Rightarrow (1+z)L_p \propto E_{iso}^{4/3}$$

$$\theta^2 \approx 1/\gamma^2 \Rightarrow \delta \approx \gamma \Rightarrow (1+z)E_p \sim (E_{iso}^{\gamma})^{2/3}$$

$$\vartheta^2 >> 1/\gamma^2 \Rightarrow \delta << \gamma \Rightarrow (1+z)E_p \sim (E_{iso}^{\gamma})^{1/3}$$

$$\Rightarrow (1+z)\cdot \mathrm{Ep} \approx \overline{\mathrm{Ep}}\cdot[(\mathrm{Eiso/Eo})^{1/3} + (\mathrm{Eiso/Eo})^{2/3}]$$

➢ identifying and understanding different classes of GRBs

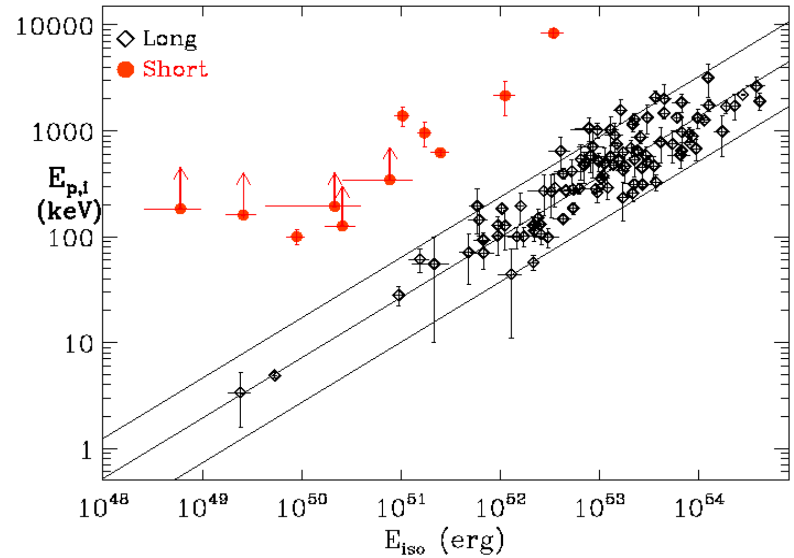


➢ *The $E_{p,i}$ – E_{iso} correlation and the short / long GRBs*

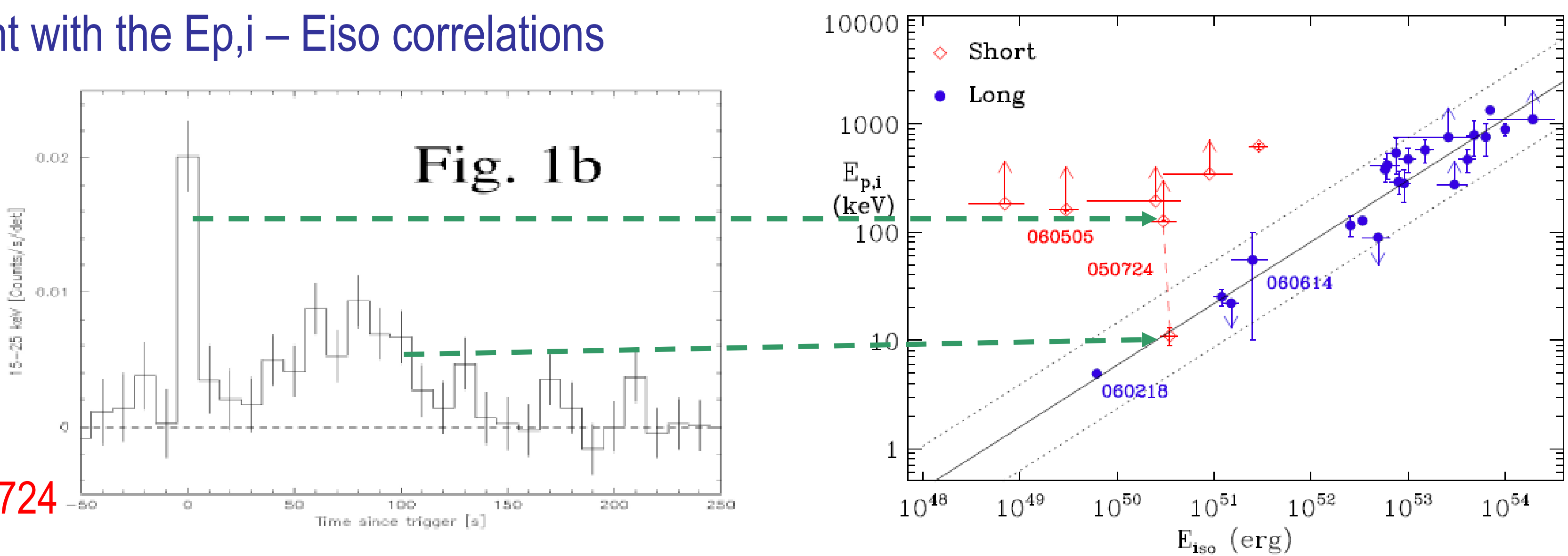
❑ only very recently, redshift estimates for short GRBs

❑ estimates and limits on Ep,i and Eiso are inconsistent with Ep,i-Eiso correlation holding for long GRBs

❑ low Eiso values and high lower limits to Ep,i indicate inconsistency also for the other short GRBs

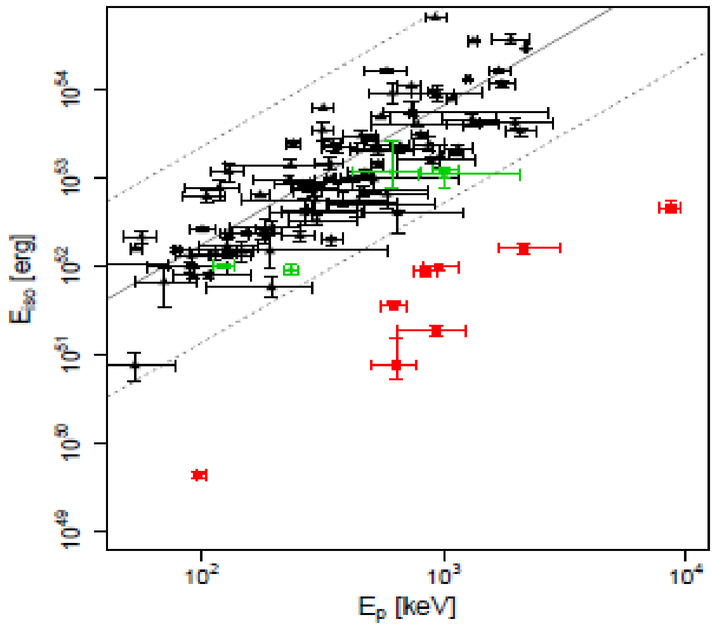


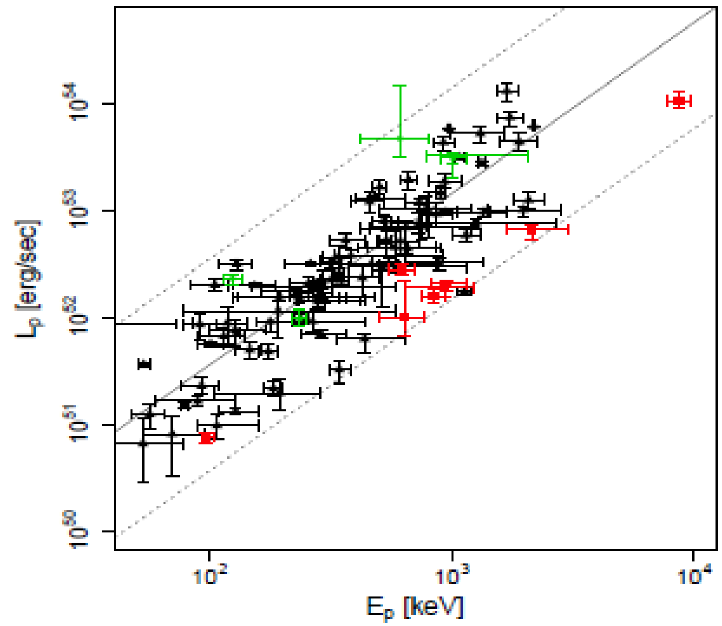
❑ long weak soft emission in some cases, consistent with the Ep,i – Eiso correlations

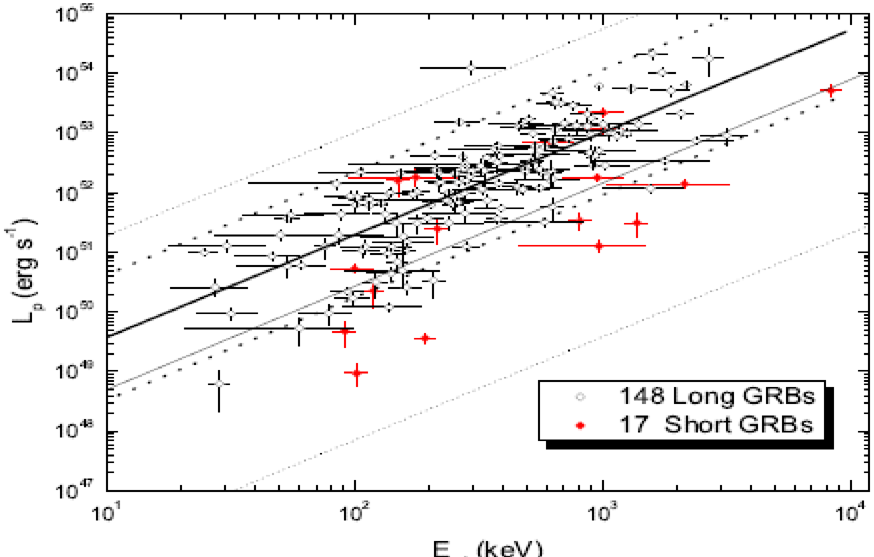


GRB0050724

❑ Different behaviour of short GRBs in the Ep,i – Eiso and Ep,i – Lp,iso planes (e.g., Ghirlanda et al. 2011, Zhang et al. 2012, Tsutsui et al. 2012)



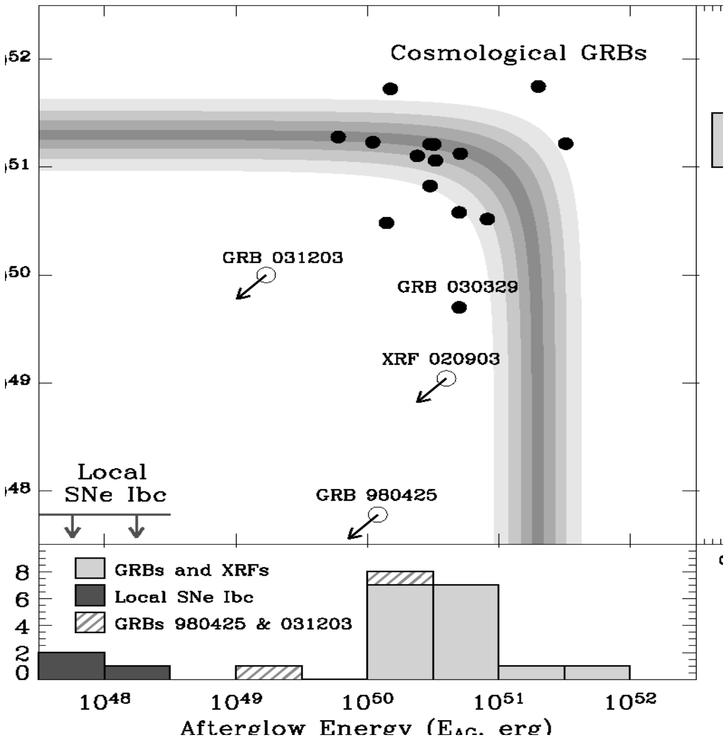


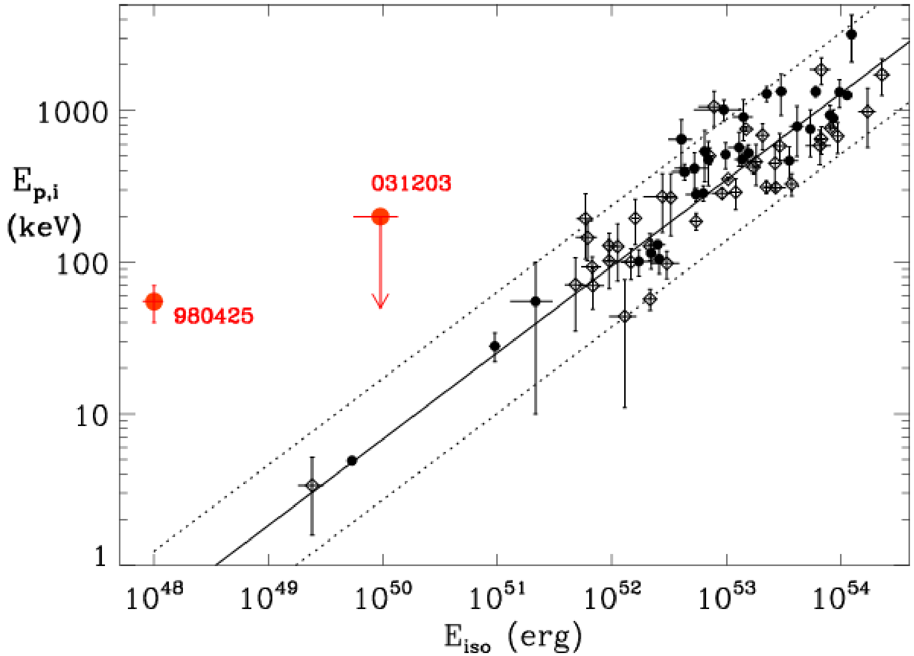


➢ The $E_{p,i}$ – E_{iso} correlation: sub-energetic GRBs and GRB/SN connection

❑ 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)

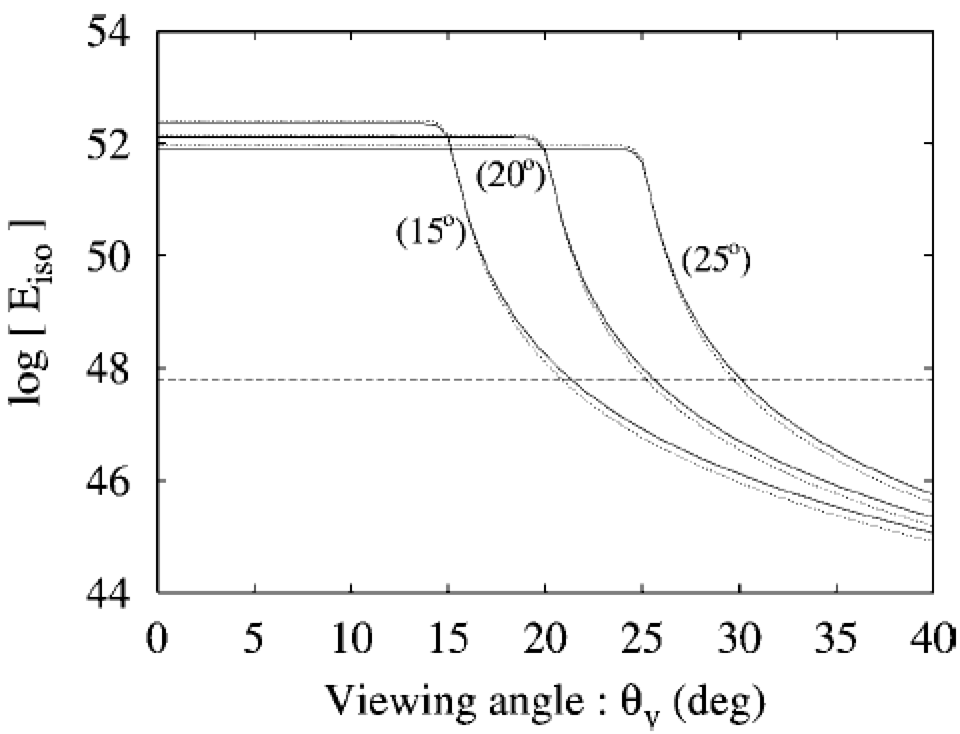
❑ GRB031203: the most similar case to GRB980425/SN1998bw: very close (z = 0.105), SN2003lw, sub-energetic



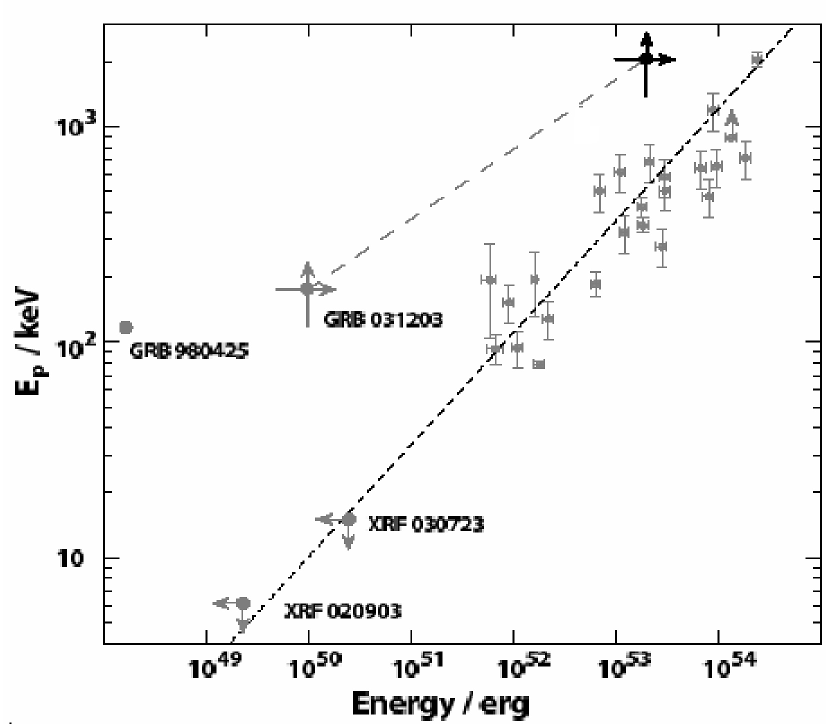


- the most common explanations for the (apparent ?) sub-energetic nature of GRB980425 and GRB031203 and their violation of the Ep,i – Eiso correlation assume that they are NORMAL events seen very off-axis (e.g. Yamazaki et al. 2003, Ramirez-Ruiz et al. 2005)
- $\delta=[\gamma(1 - \beta\cos(\theta v -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

  $\alpha=1\div2.3$ -> $\Delta Eiso \propto \delta^{(2 \div 3.3)}$



Yamazaki et al., ApJ, 2003

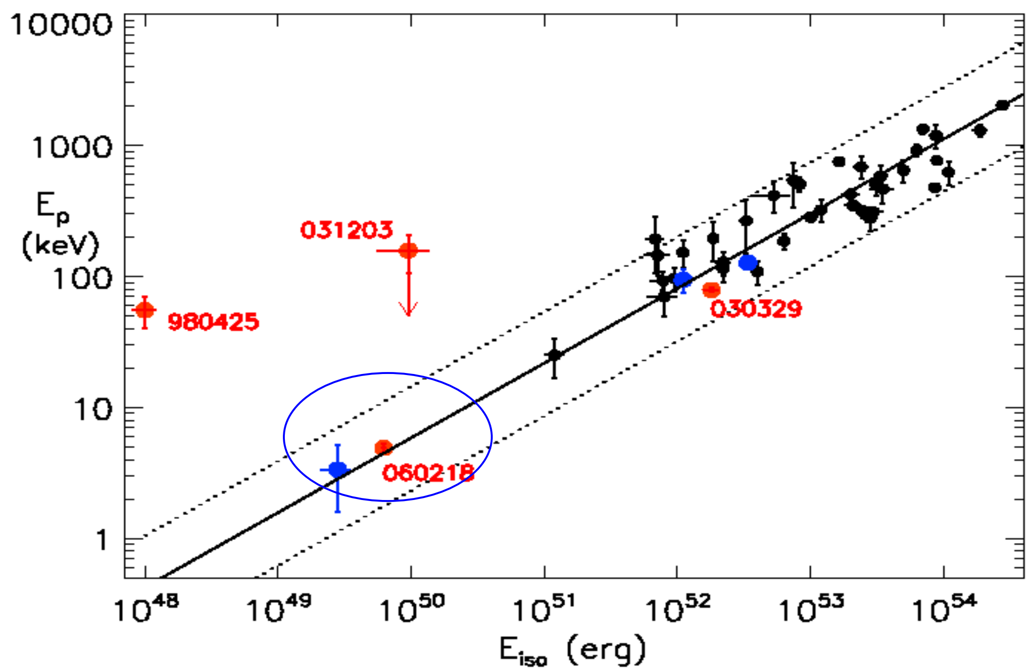


Ramirez-Ruiz et al., ApJ, 2004

- 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

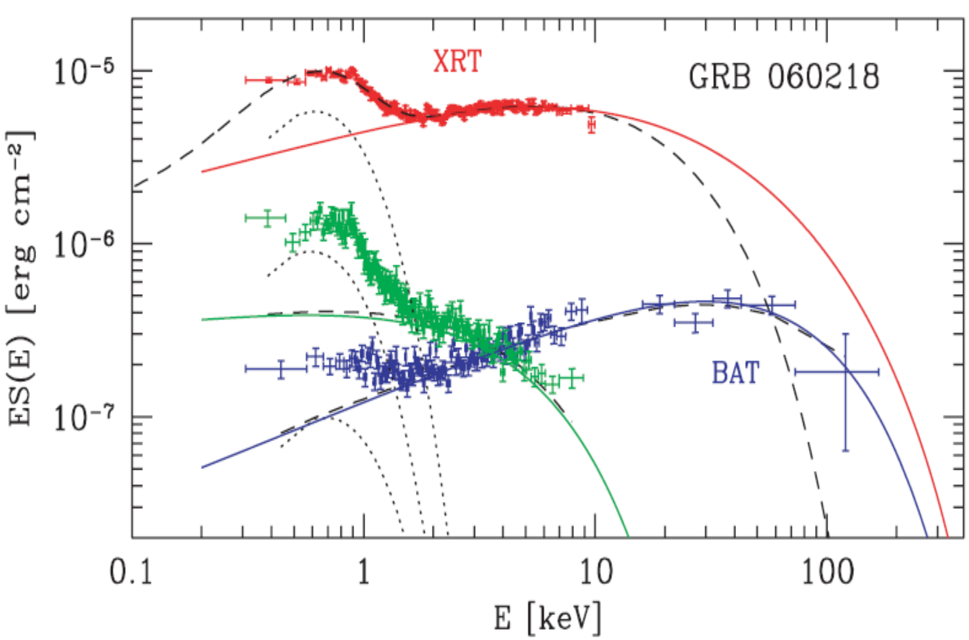


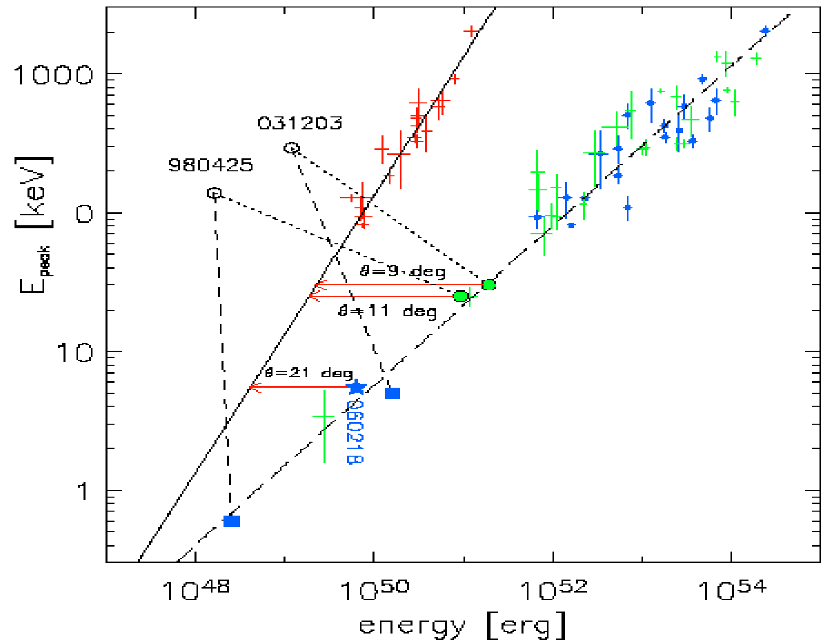
Amati et al., 2007

- 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

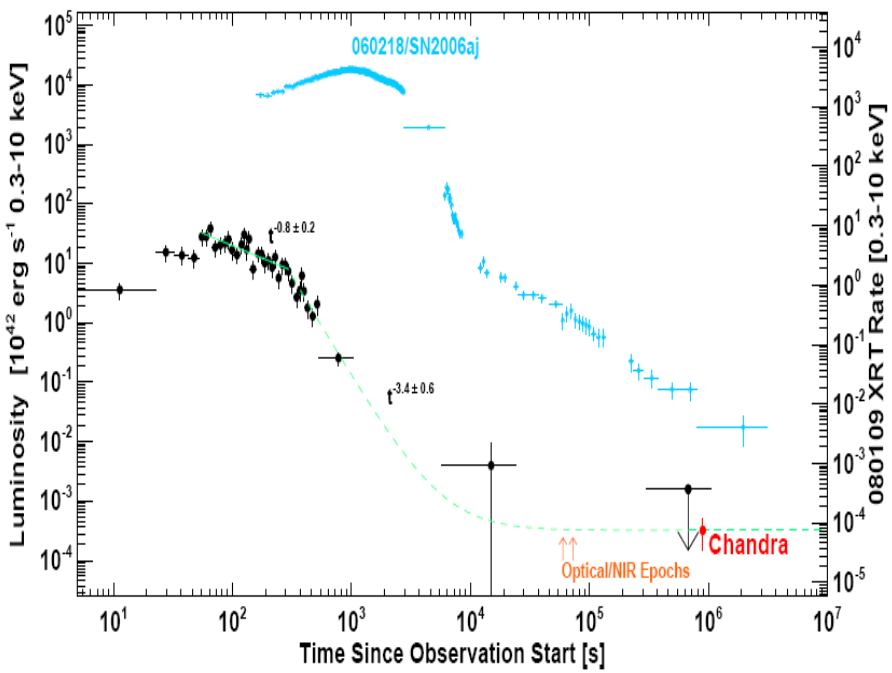
- Ghisellini et al. (2006) found that a spectral evolution model based on GRB060218 can be applied to GRB980425 and GRB031203, showing that these two events may be also consistent with the Ep,i-Eiso correlation

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

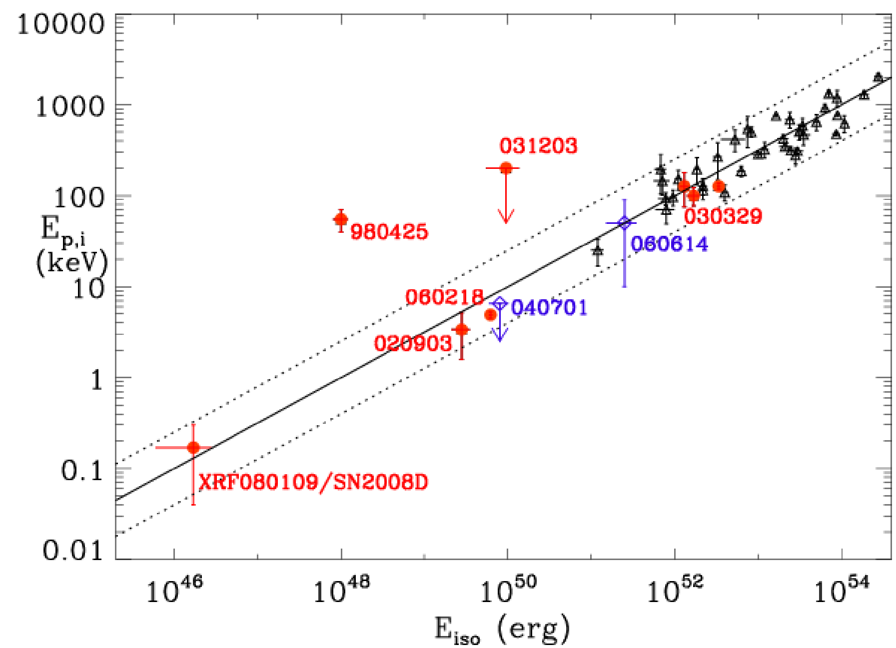




- Recent Swift detection of an X-ray transient associated with SN 2008D at z = 0.0064, showing a light curve and duration similar to GRB 060218
- Debate: very soft/weak XRF or SN shock break-out ?
- Peak energy limits and energetics consistent with a very-low energy extension of the Ep,i-Eiso correlation (Li 2008, based on XRT and UVOT data)
- Evidence that this transient may be a very soft and weak GRB (XRF 080109), thus confirming the existence of a population of sub-energetic GRB ?



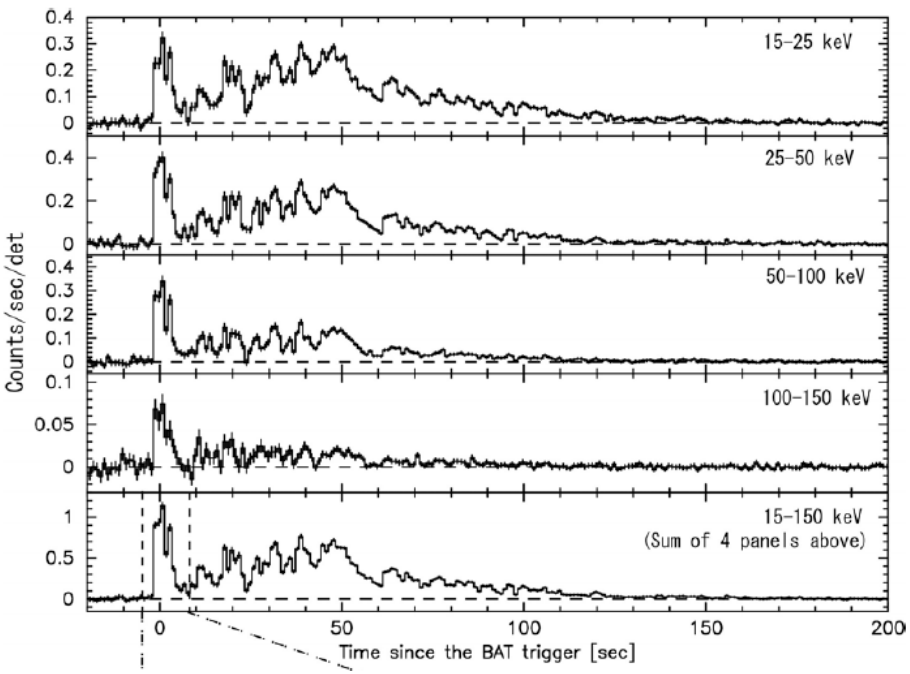
Modjaz et al., ApJ, 2008

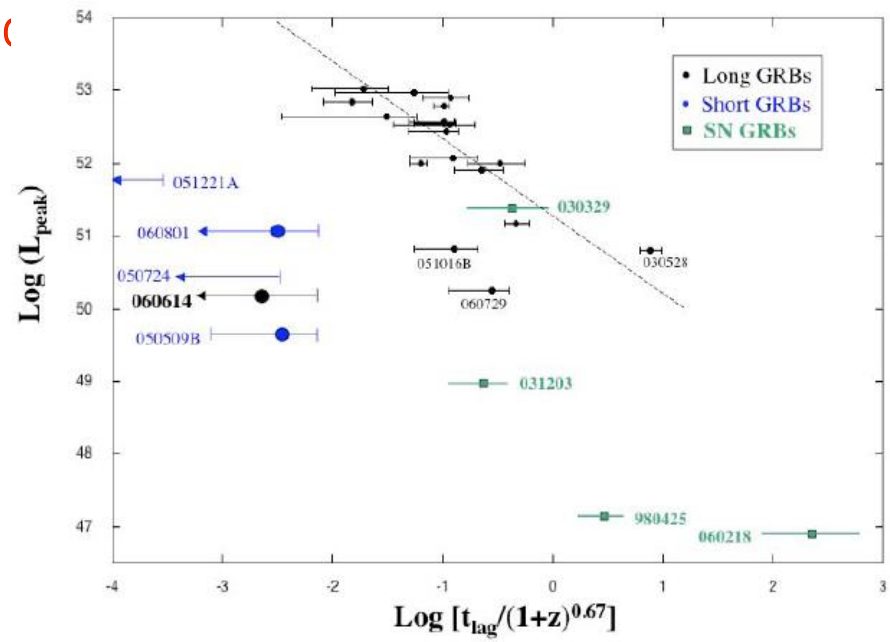


Amati, 2009

- The intriguing issue of GRB 060614: a close and long GRB with a deep upper limit to the magnitude of associated SN

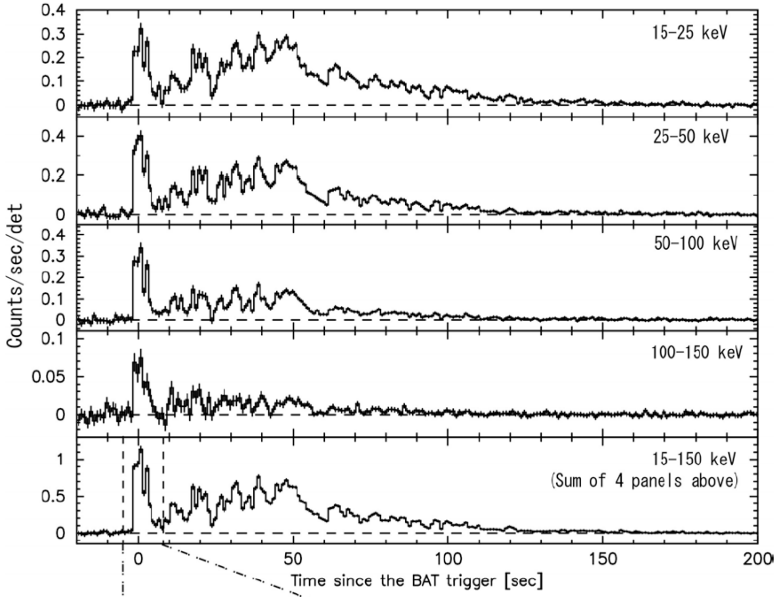
- light curve with initial short-like pulse and prominent long soft tail
- in the spectral lag – peak luminosity plane, GRB060614 lies in the short GRBs region
- Based on this, Gehrels et al. propose that GRB 060614 has similar properties to short GRBs and propose a new GRB classification scheme
- they also report that the first pulse (Ep,i from Konus-Wind) does not follow the Ep.i-Eiso correlation, further supporting the similarity with short GRBs (but to check consistency with

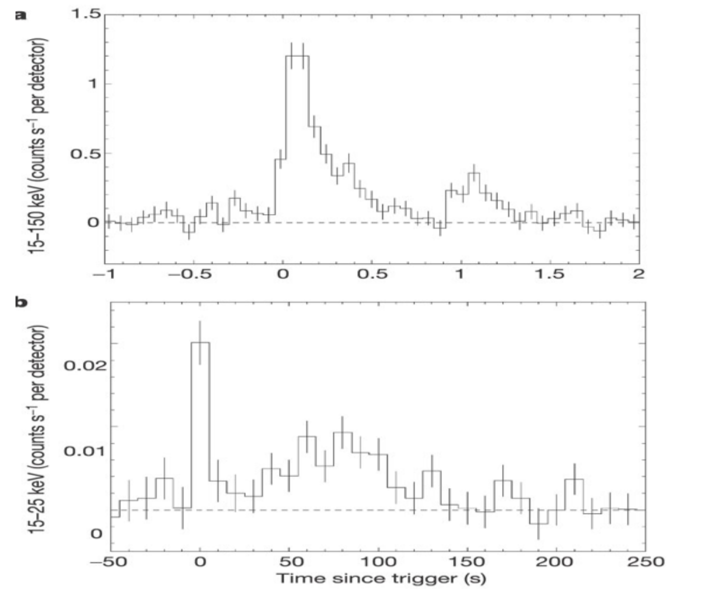


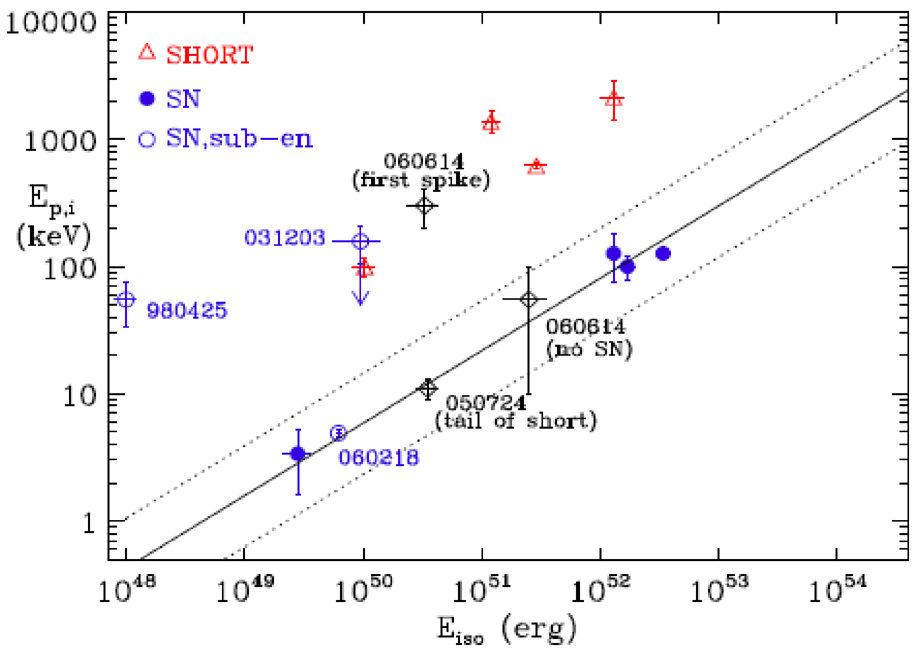


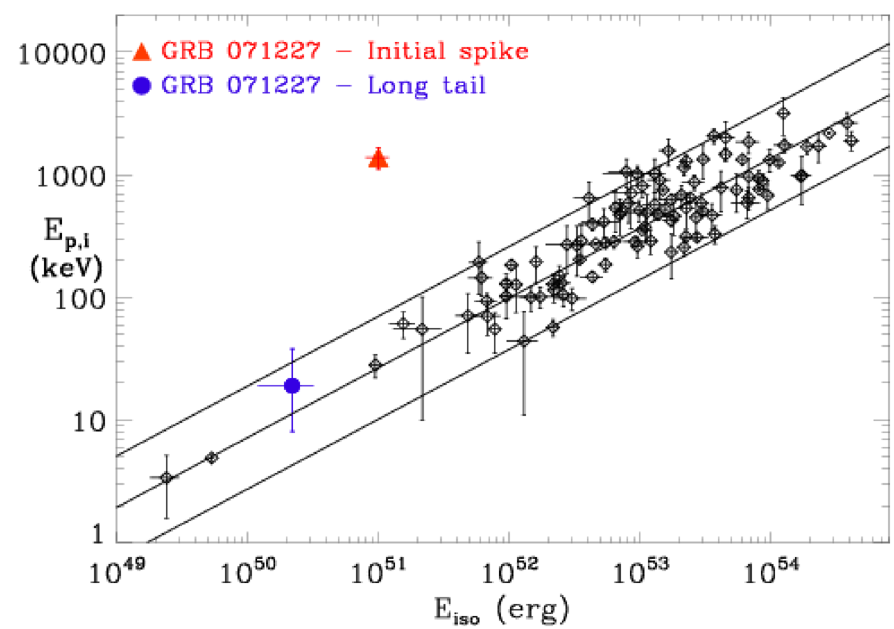
Gehrels et al., Nature, 2006

❑ Initial pulse and long tail of GRB 060614 in behave in the Ep,i – Eiso plane like short GRBs



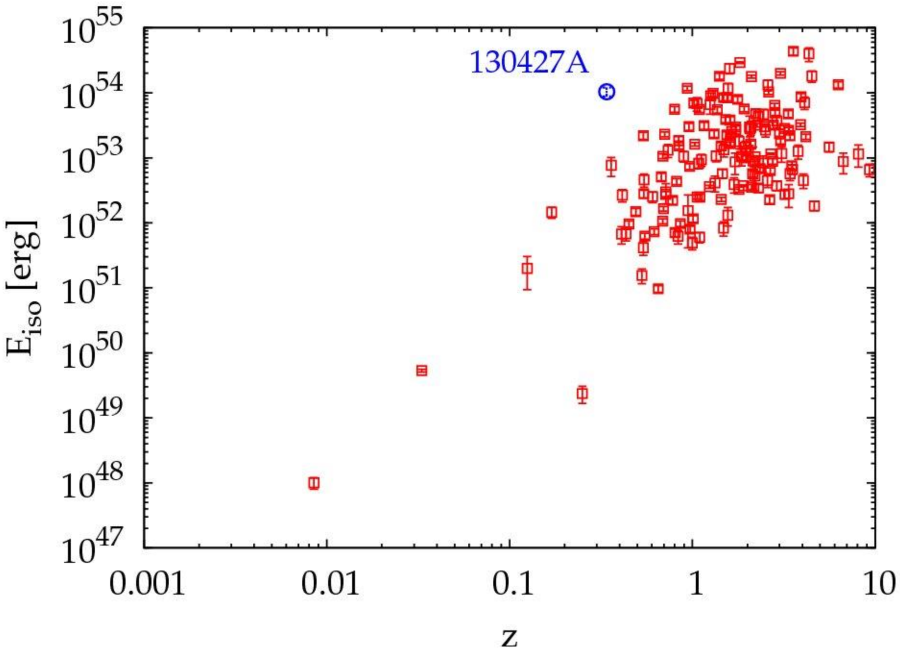


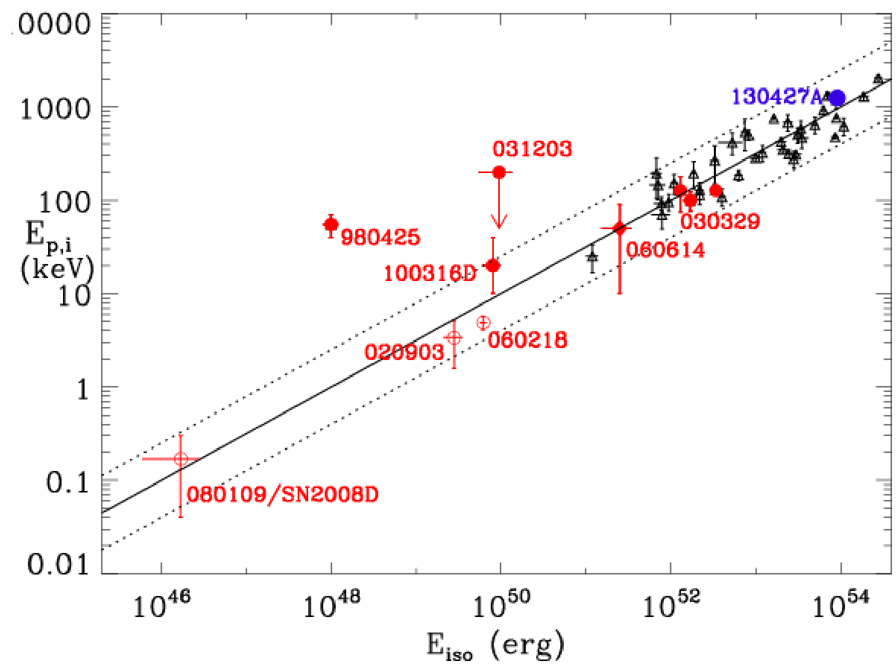




❑ Testing the GRB-SN paradigm with the brightest "close" event; GRB 130427A

- Recent detection of the very energetic (Eiso = 10^{54} erg) "neraby" (z = 0.34) GRB030427A
- Unique occasion to test the GRB-SN connection (up to now, only nearby and weak GRBs)





➢ Using the Ep,i-Eiso correlation to infer limits or ranges for redshift

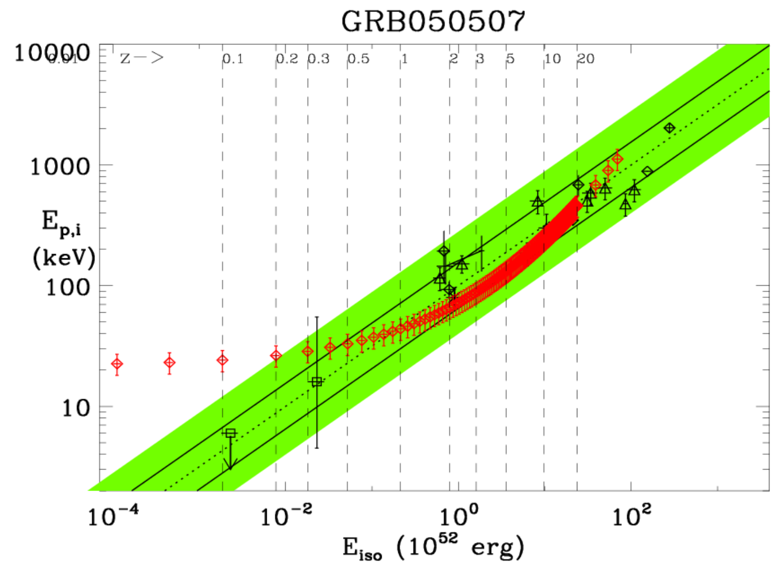
- ❑ redshift estimates available only for a small fraction of GRBs occurred in the last 10 years based on optical spectroscopy

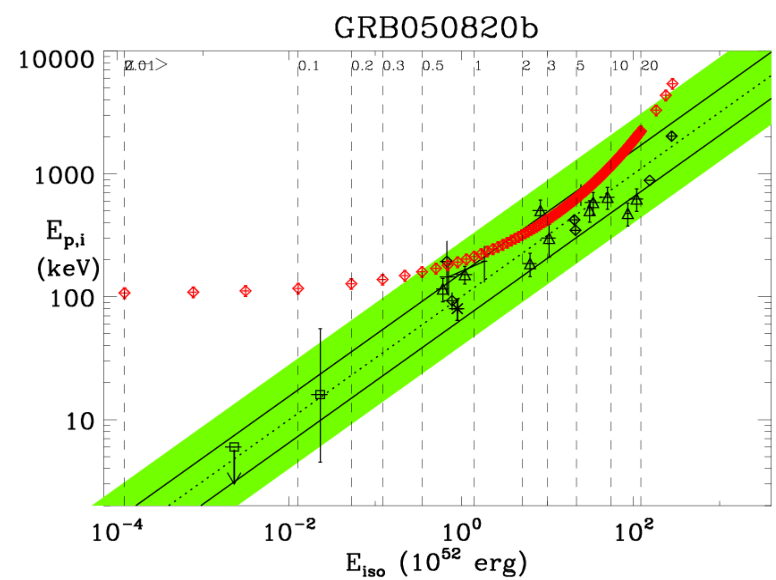
- ❑ pseudo-redshift estimates for the large amount of GRB without measured redshift -> GRB luminosity function, star formation rate evolution up to z > 6, etc.

- ❑ use of the Ep,i – Eiso correlation for pseudo-redshift: most simple method is to study the track in the Ep,i - Eiso plane ad a function of z

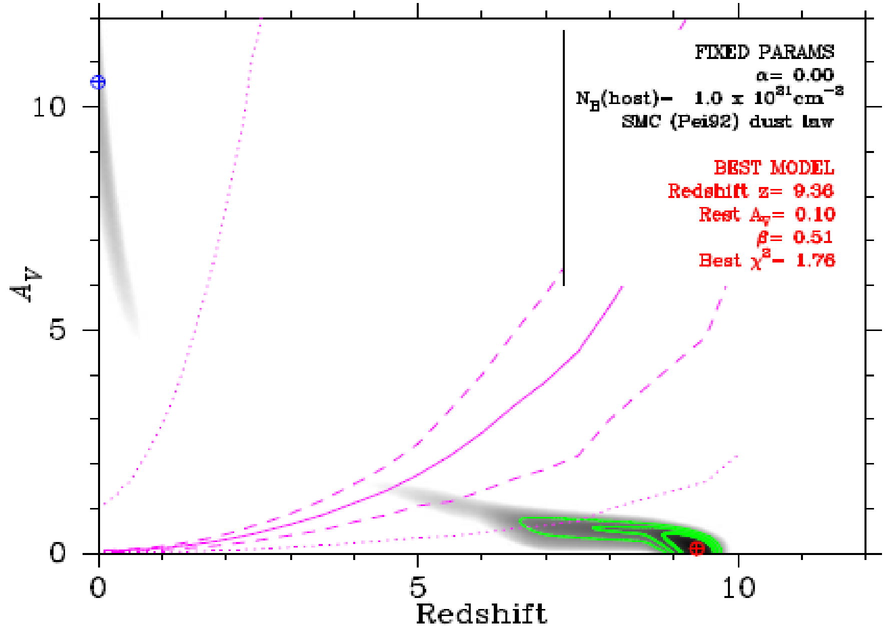
- ❑ not precise z estimates and possible degeneracy for z > 1.4

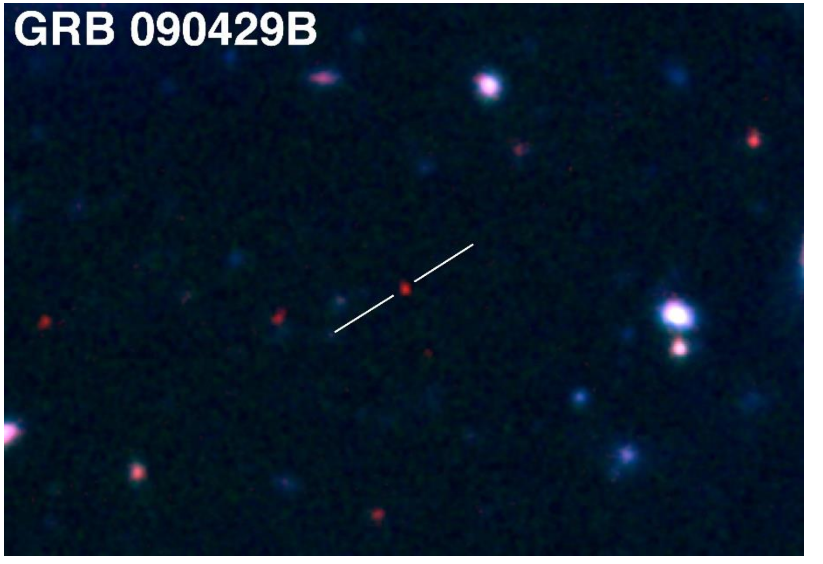
- ❑ anyway useful for low z GRB and in general when combined with optical

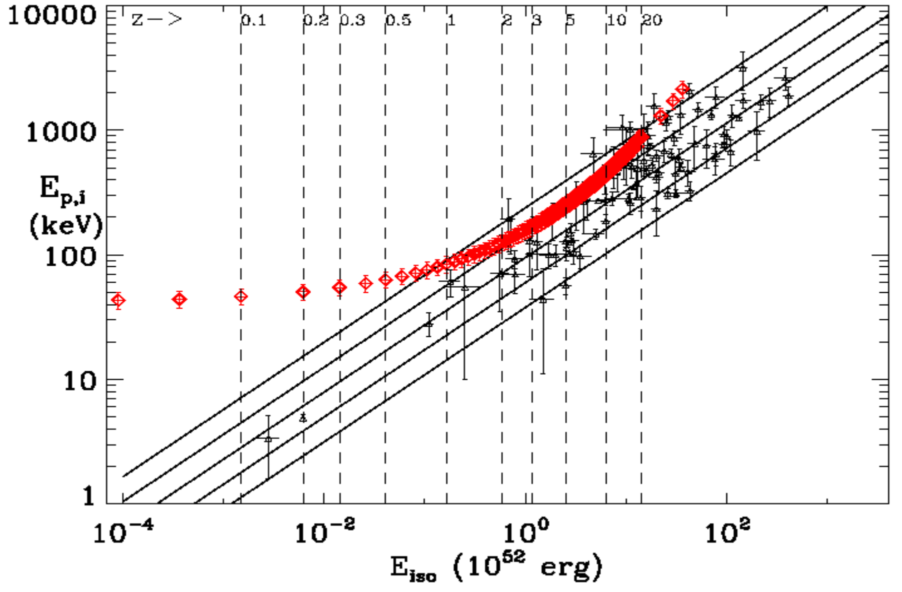


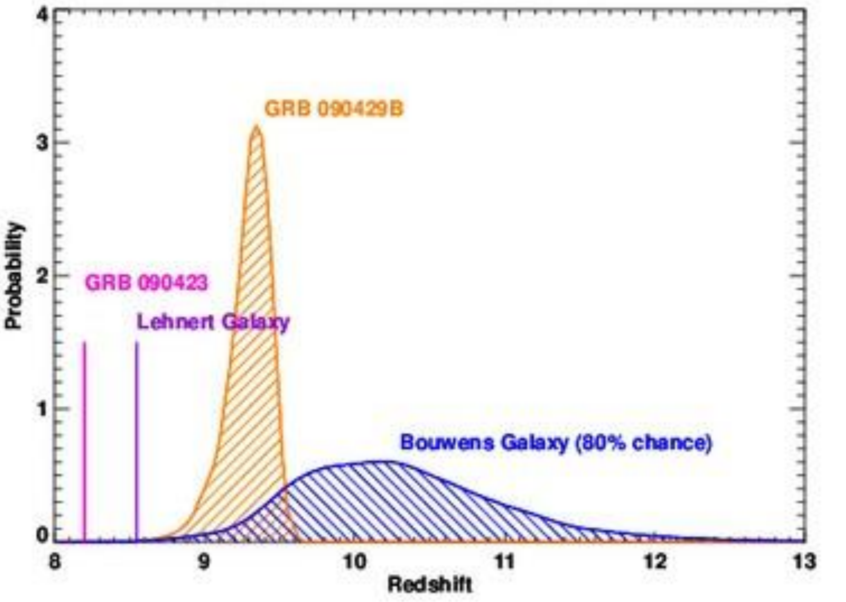


❑ The case of GRB 090429B at a photometric redshift of ~9.4 ! (Cucchiara et al. 2011): a (pop III ?) star exploded at only 500 millions years since big-bang









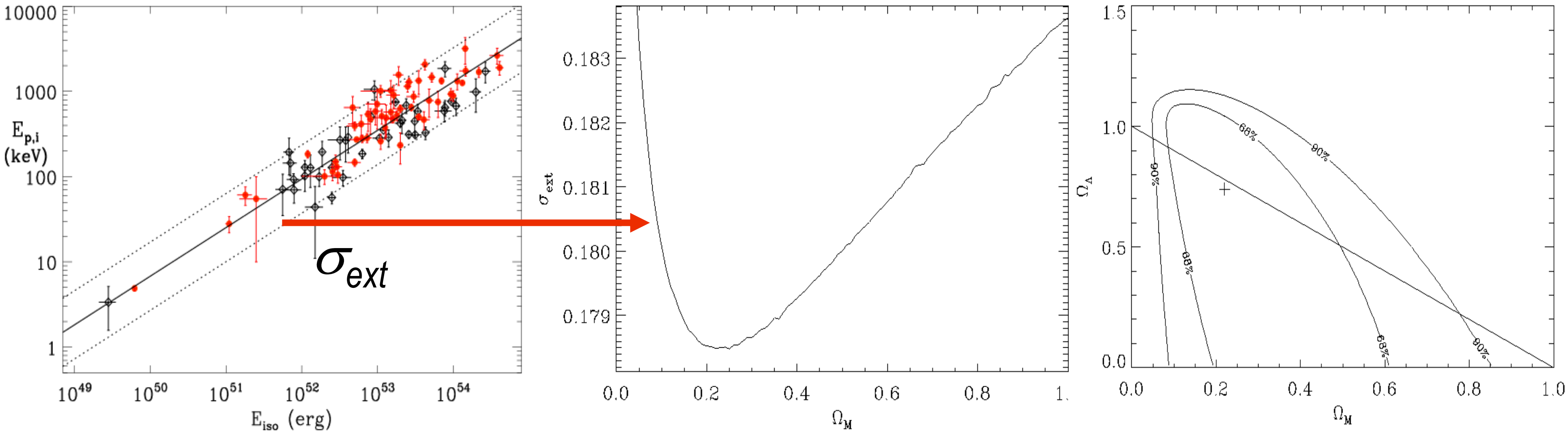
➢ GRB cosmology ?

- GRB have huge luminosities and a redshift distribution extending far beyond SN Ia and even beyond that of AGNs
- high energy emission -> no extinction problems
- **potentially powerful cosmological sources**
- estimate of cosmological parameters through spectrum-energy correlations ?

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

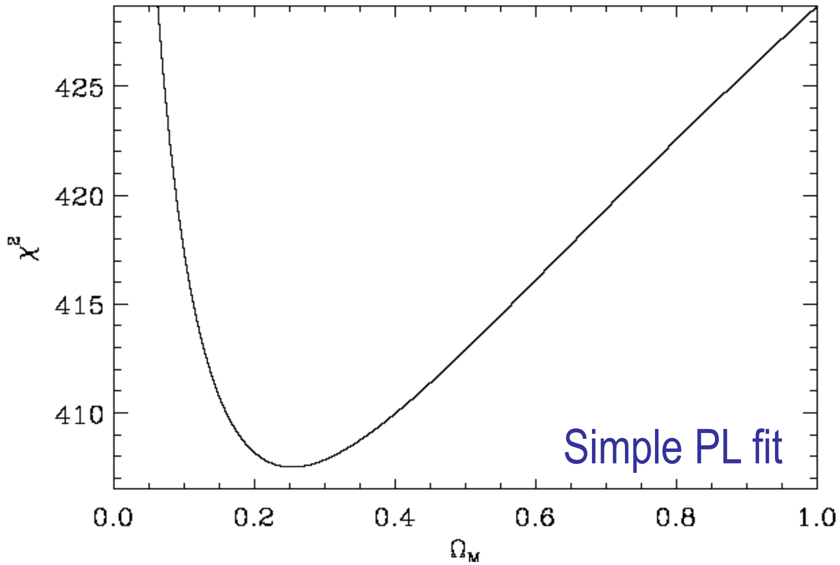
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \text{erg}$$

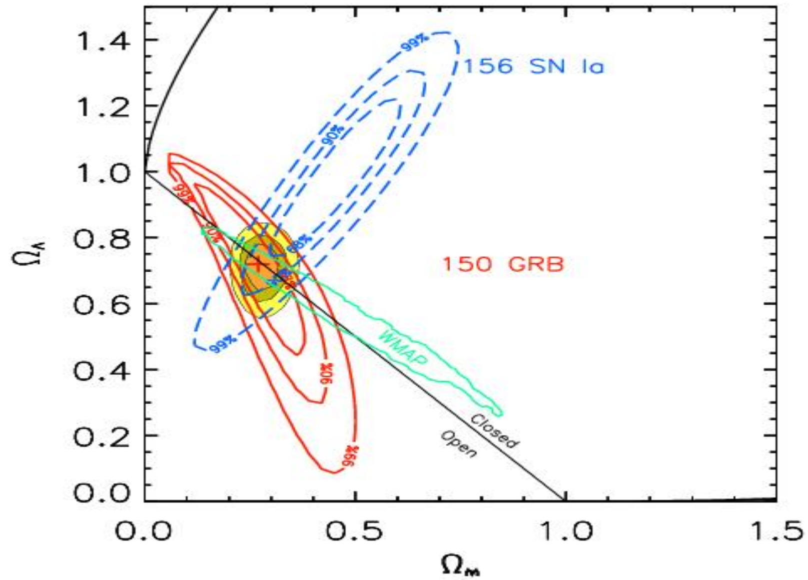
$$D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$

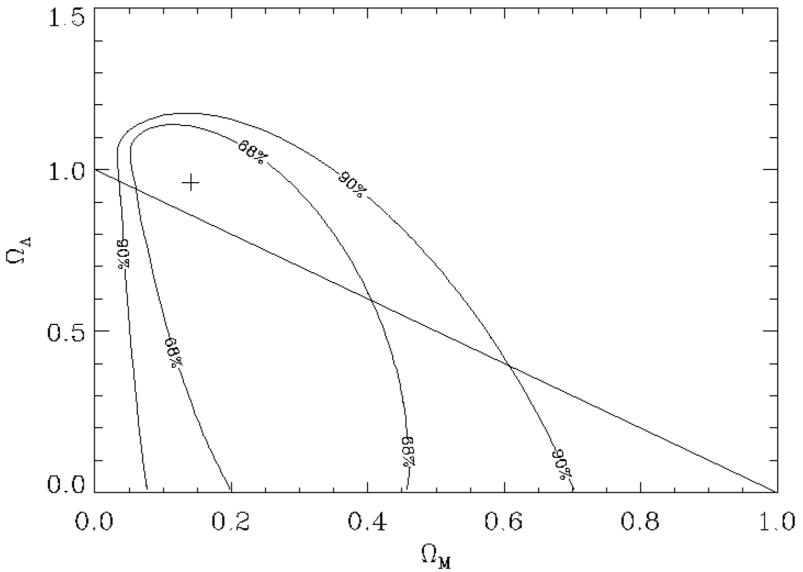


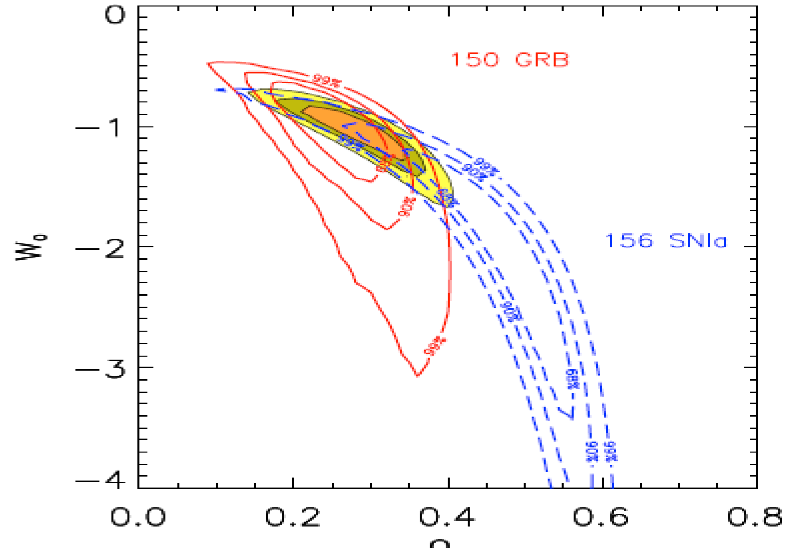
Amati et al. 2008, 2009

➢ implications and uses: GRB cosmology









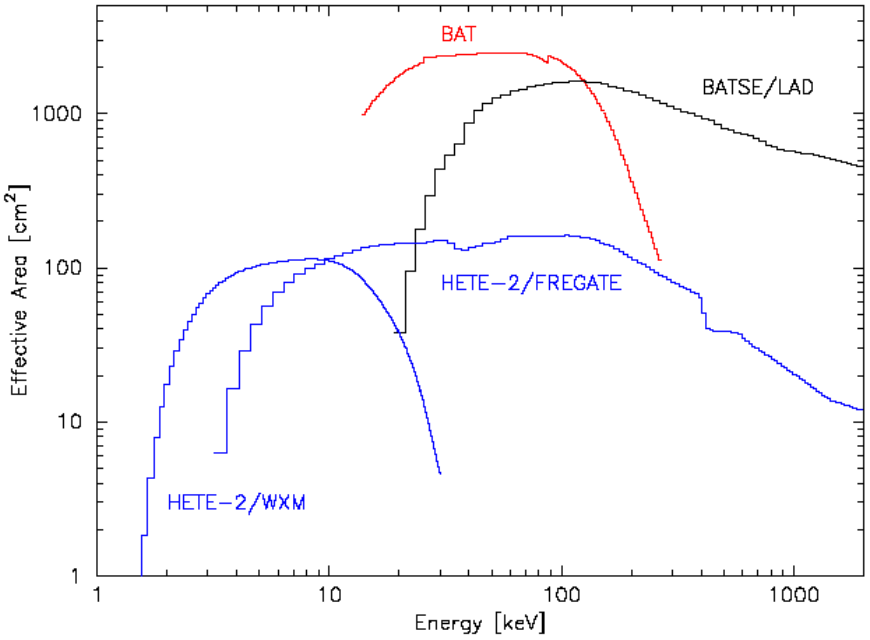
Amati et al. 2008, 2012

Ghirlanda, Ghisellini et al. 2005, 2006,2007

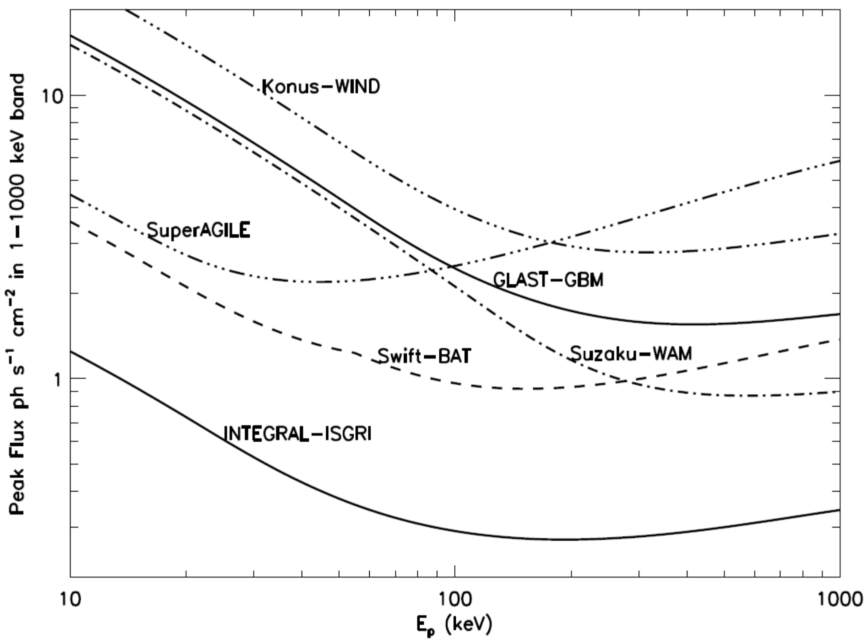
Instrumental/selection effects, systematics, outliers

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

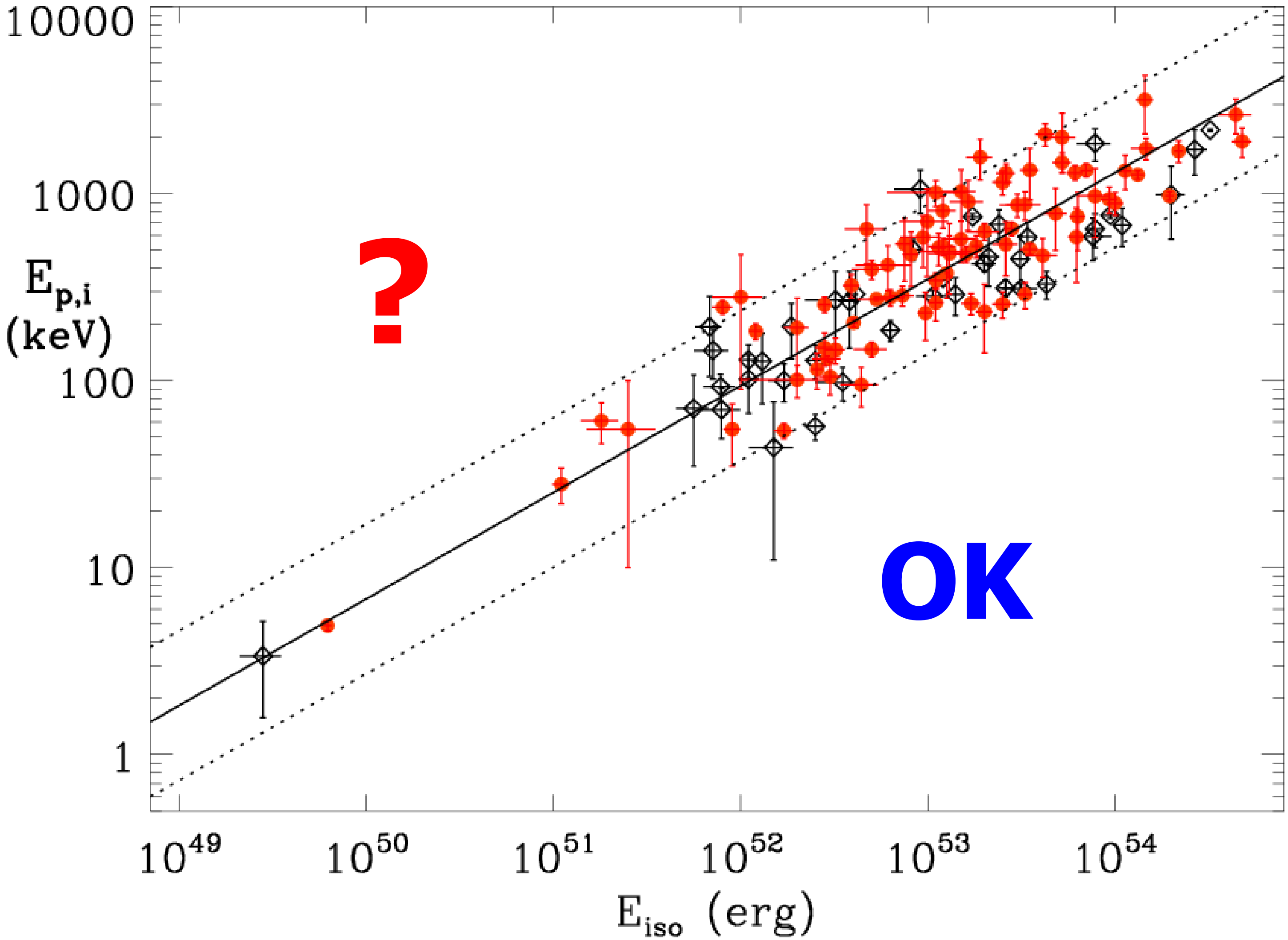
- this may introduce relevant selection effects / biases in the observed Ep,i – Eiso and other correlations



Sakamoto et al. 2011

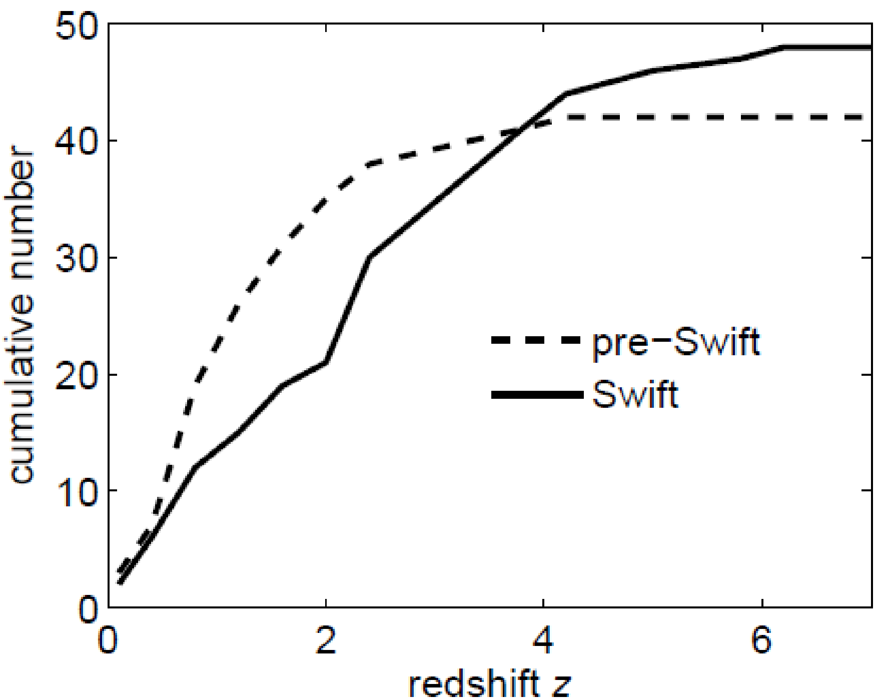


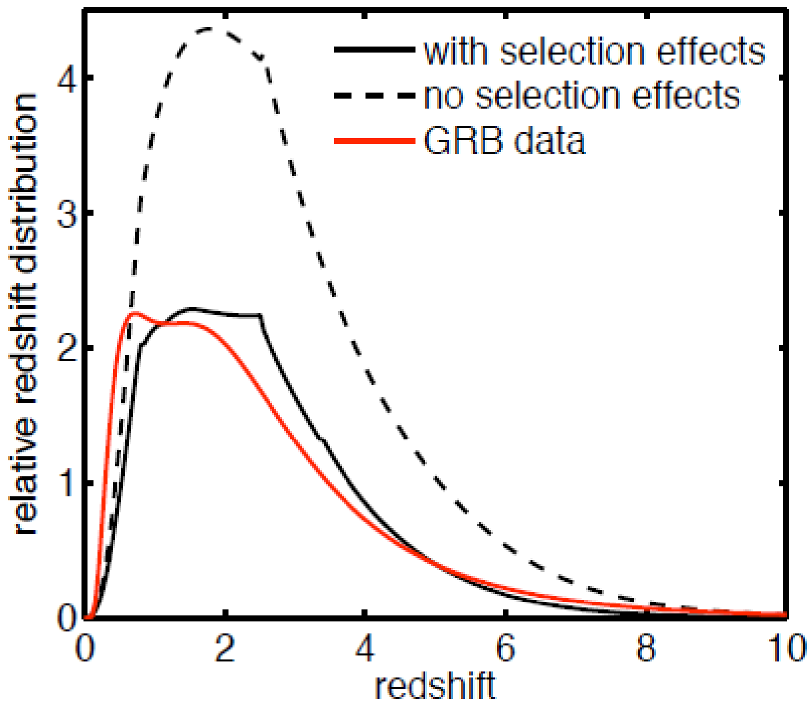
Band 2008



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)

➢ selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, 2013 Jakobbson et al. 2010)

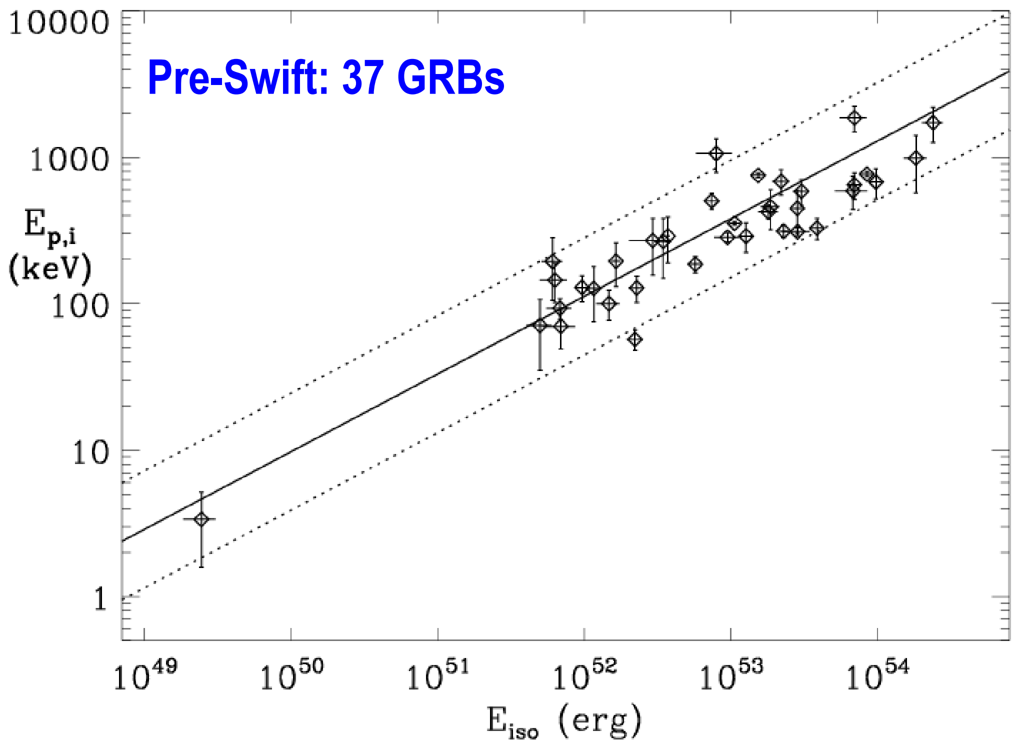




GRBs WITH measured redshift

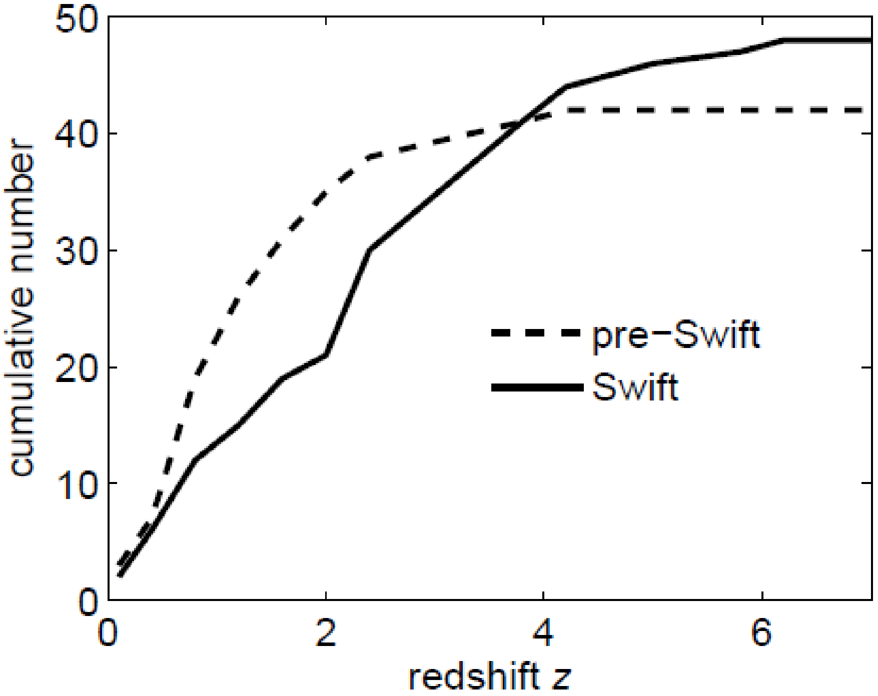
❑ Swift era: substantial increase of the number of GRBs with known redshift: ~45 in the pre-Swift era (1997-2003), ~230 in the Swift era (2004-2012)

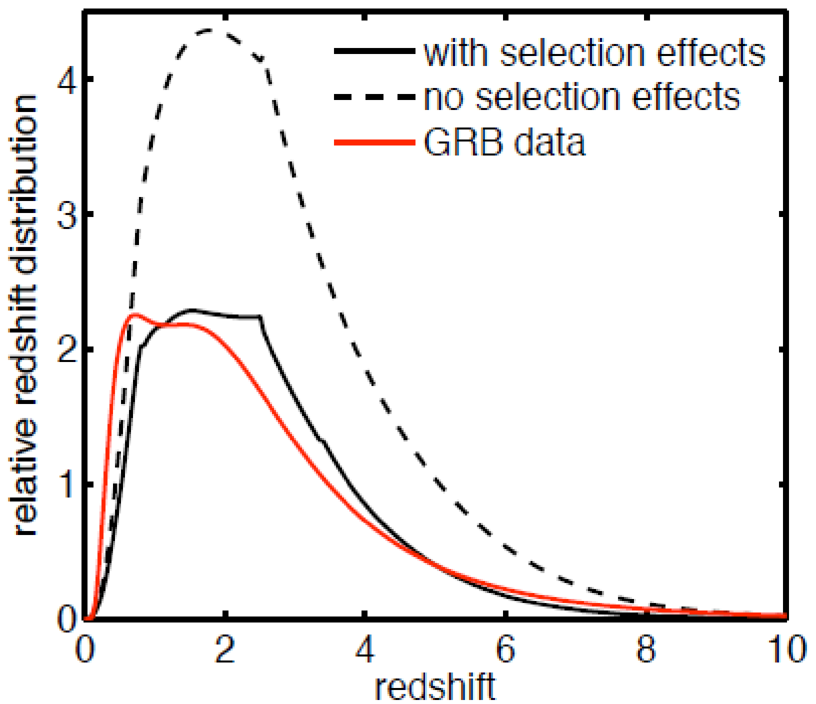
➢ thanks also to combination with other GRB experiments with broad energy band (e.g., Konus/WIND, Fermi/GBM), **substantial increase of GRBs in the Ep,i – Eiso plane**



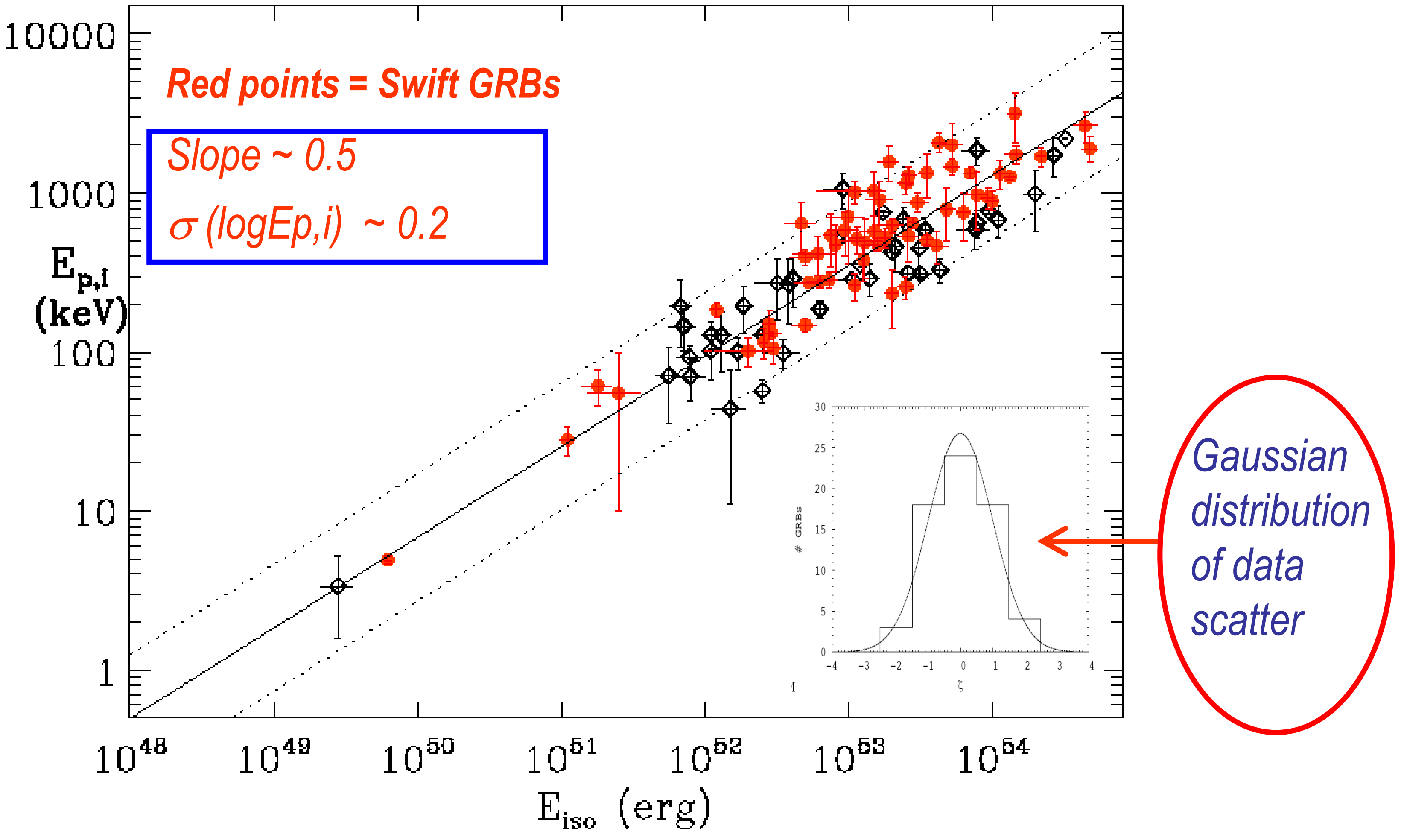
➢ selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, 2013, Jakobbson et al. 2010)

➢ Swift: reduction of selection effects in redshift -> Swift GRBs expected to provide a robust test of the Ep,i – Eiso correlation





➢ 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**



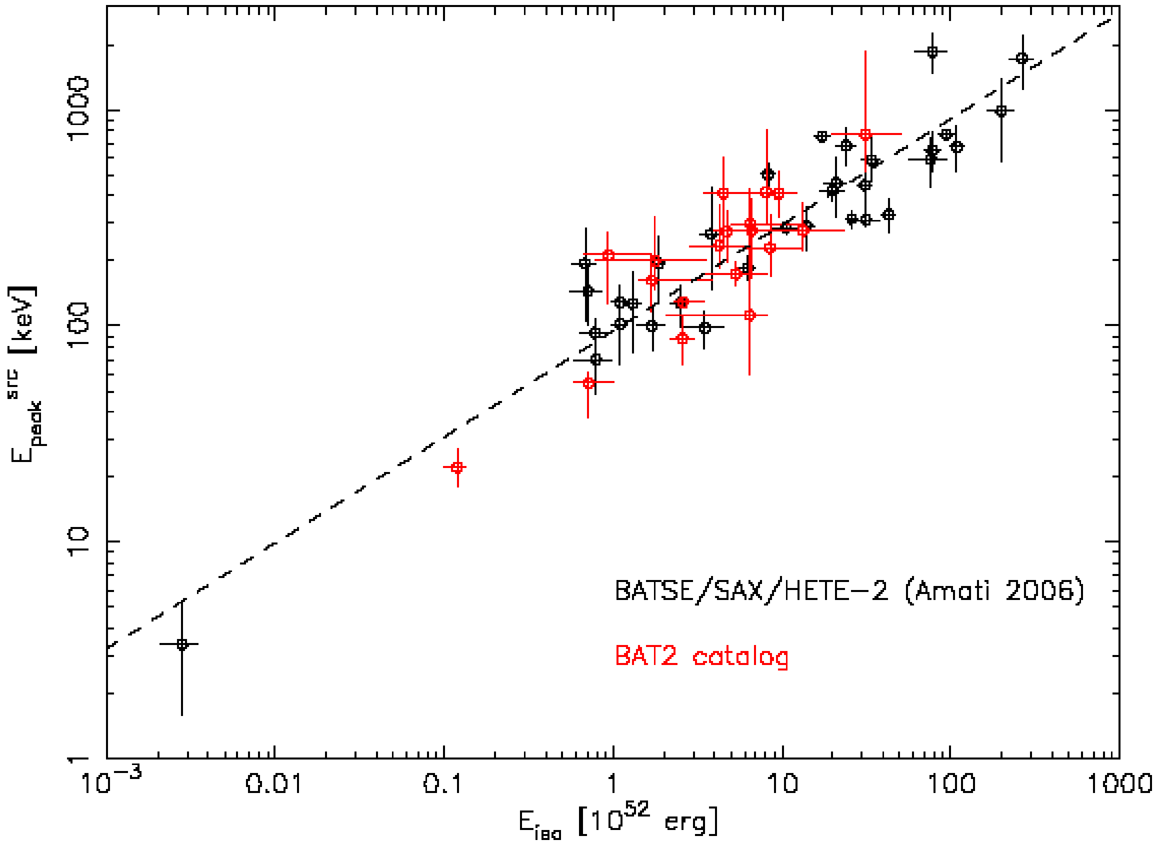
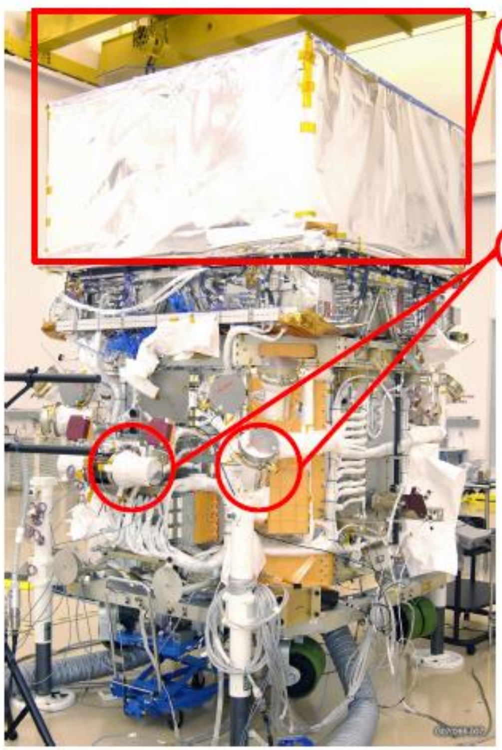


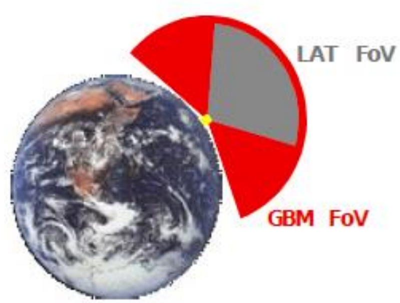
Fig. 33.— The correlation between $E^{\rm src}_{\rm peak}$ and $E_{\rm iso}$ for the *Swift* GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E^{\rm src}_{\rm peak}$ and $E_{\rm iso}$ reported by Amati (2006): $E^{\rm src}_{\rm peak} = 95 \times (E_{\rm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

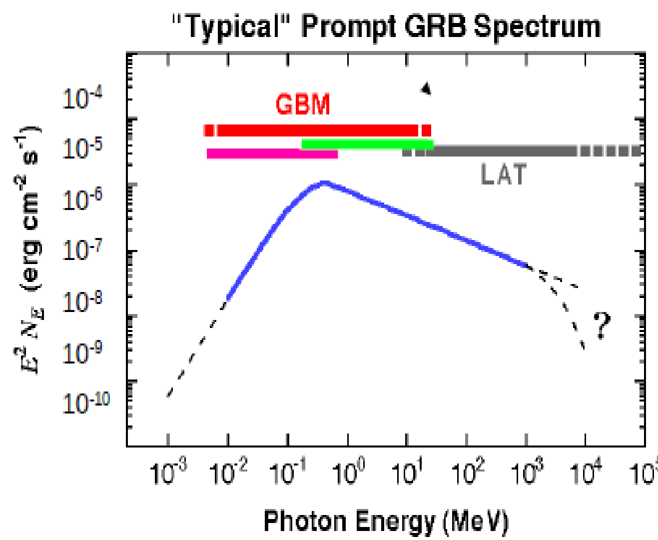
Sakamoto et al. 2011

- 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**



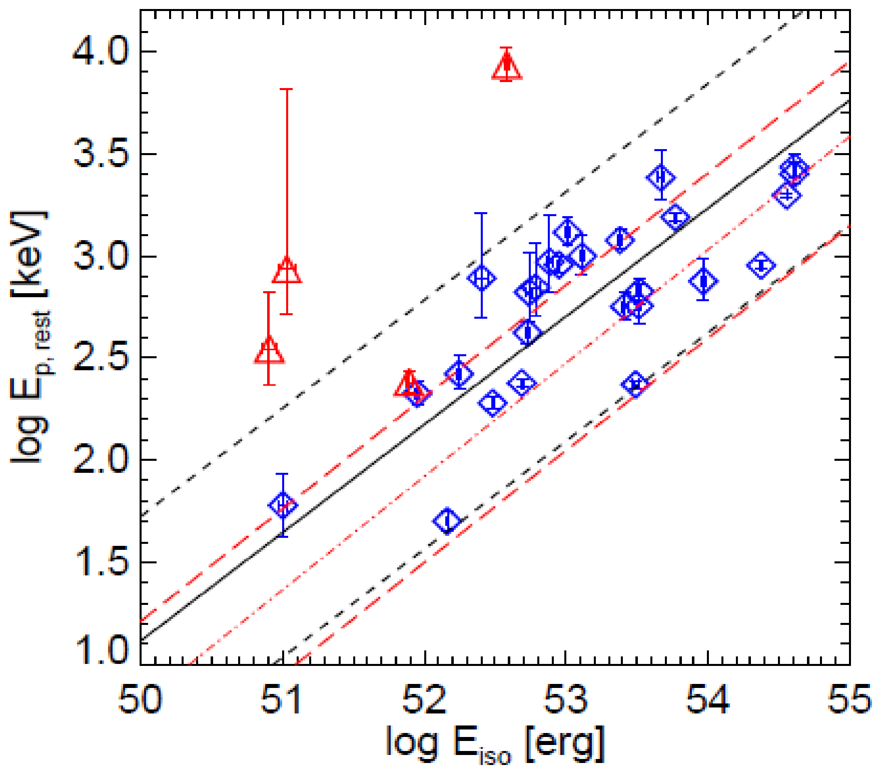
- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.

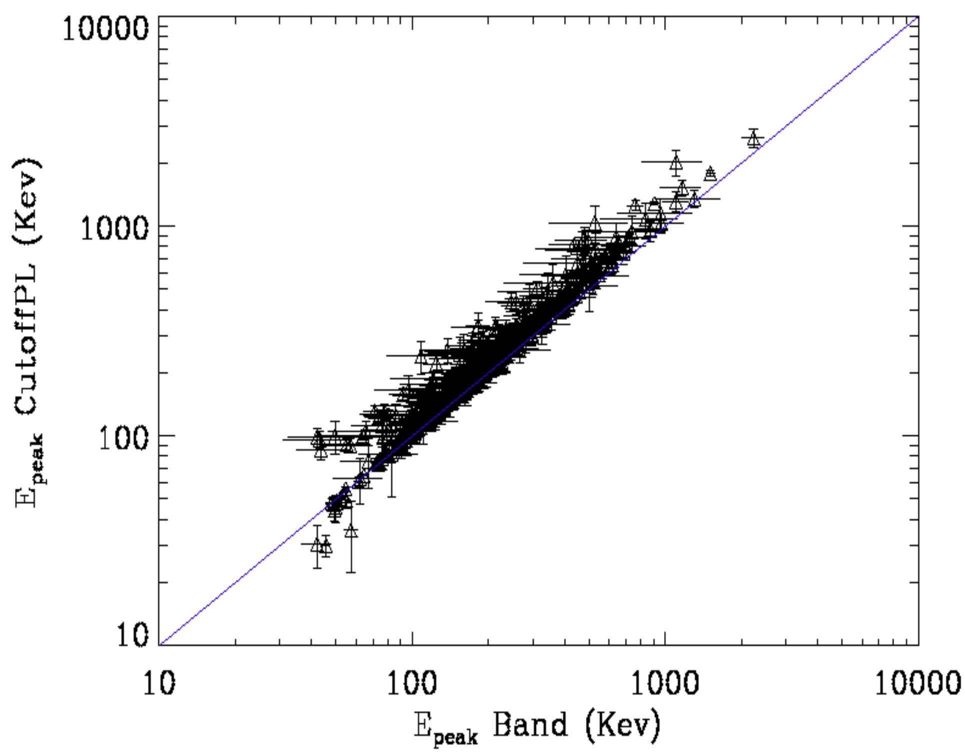




- *Gruber et al (2011, official Fermi team): all Fermi/*GBM long GRBs with known z are consistent with Ep,i – Eiso correlation, short GRBs are not

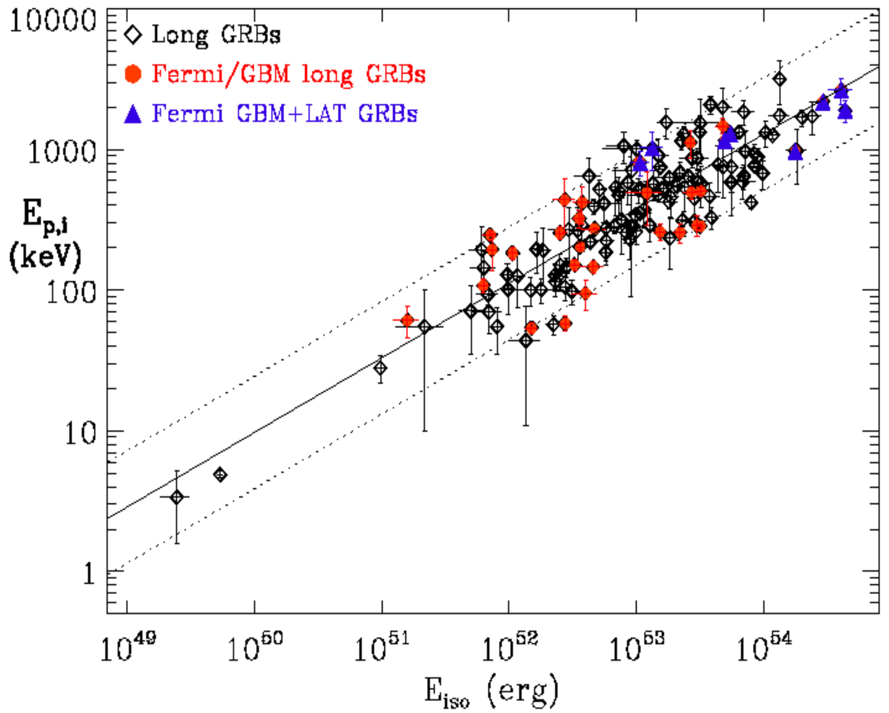
- slight overestimate of normalization and dispersion possibly due to the **use, for some GRBs, of the CPL model instead of the Band model (-> overestimate of Ep, underestimate of Eiso)**



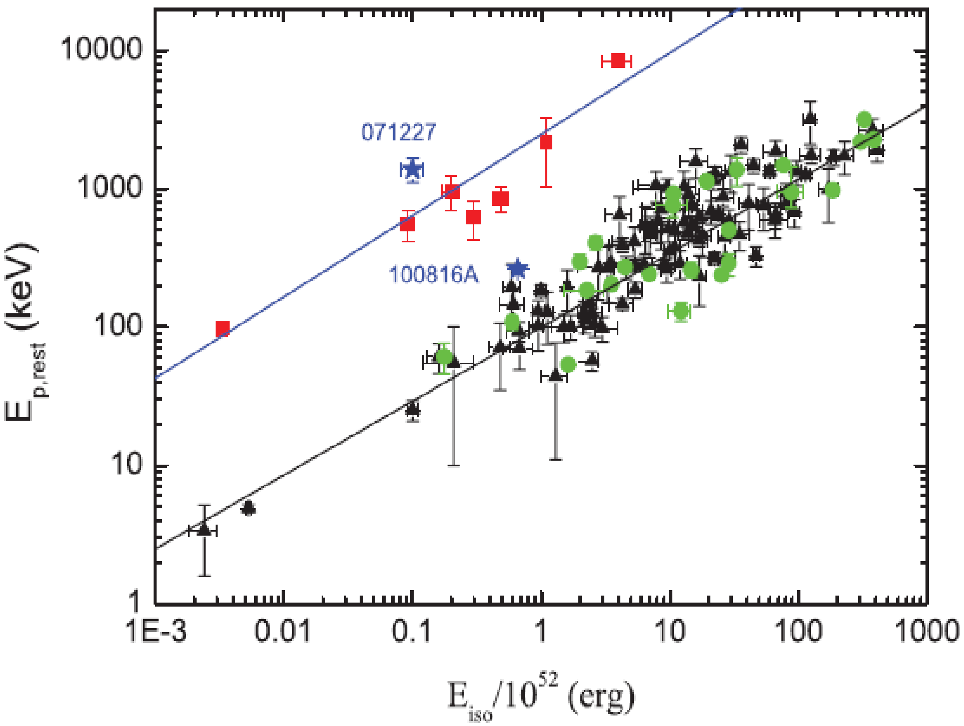


Gruber et al. 2011

❑ 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)

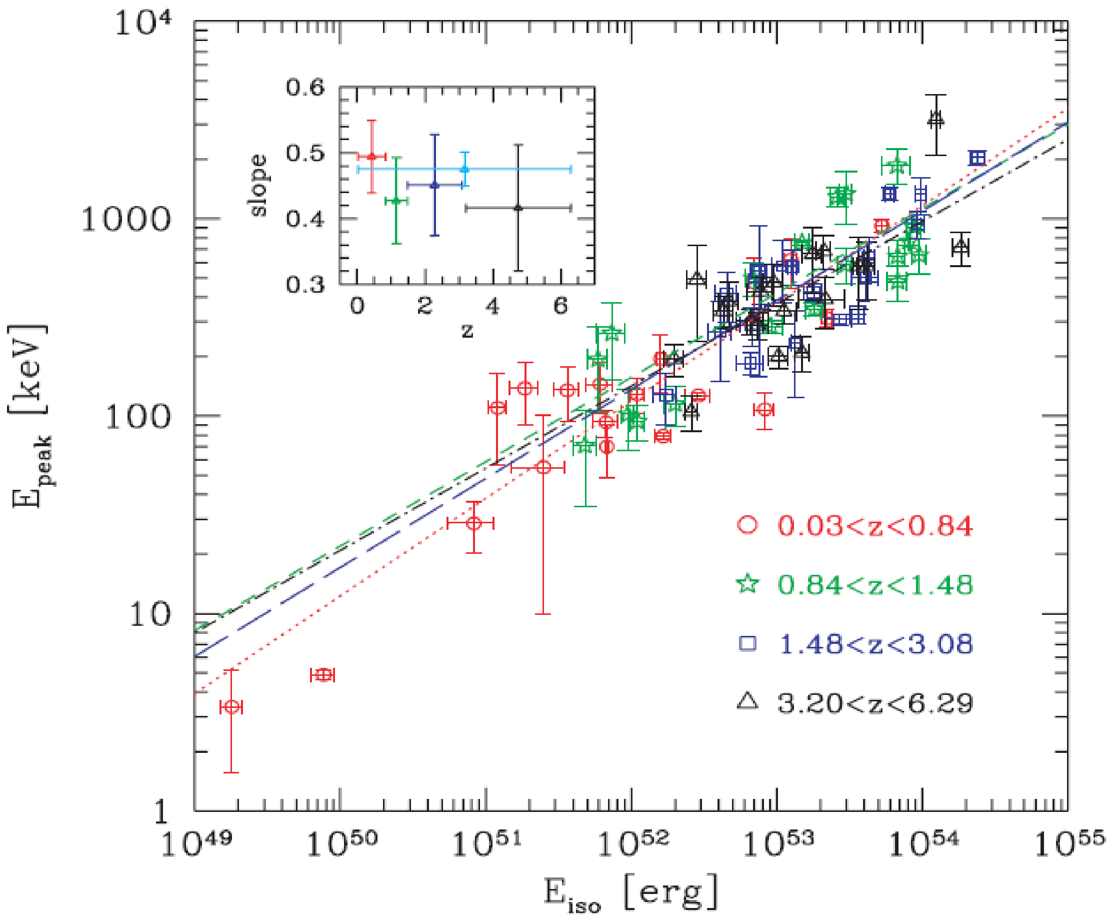


Amati 2012



Zhang et al. 2012

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



Ghirlanda et al. 2008

GRBs WITHOUT measured redshift

- claims that a high fraction of BATSE events **(without z)** are inconsistent with the correlation (e.g. Nakar & Piran 2004, 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**

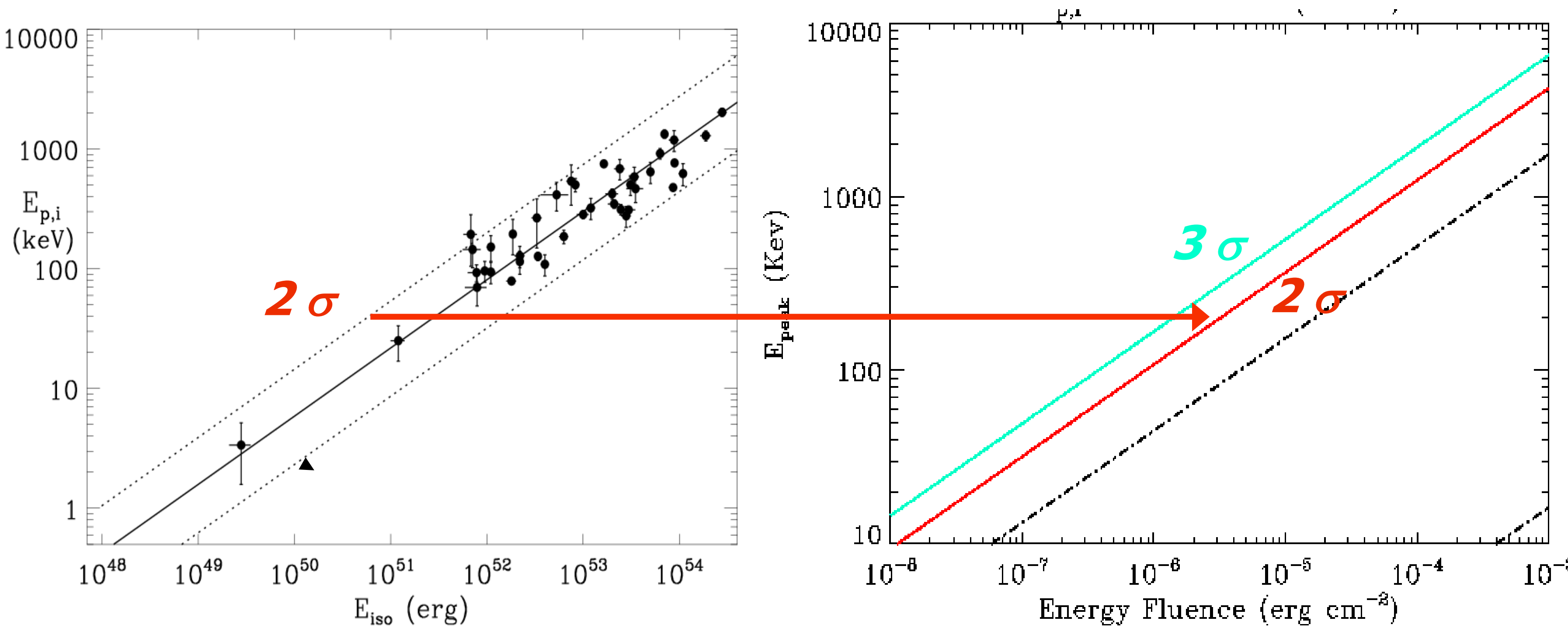
- moreover: the existence of an Ep,i – Eiso correlation was supposed by Lloyd, Petrosian & Mallozzi in 2001 **based on BATSE data**

- **Substantially different conclusions, but… data are data, it cannot be a matter of opinions !**

❑ method: 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 (140)

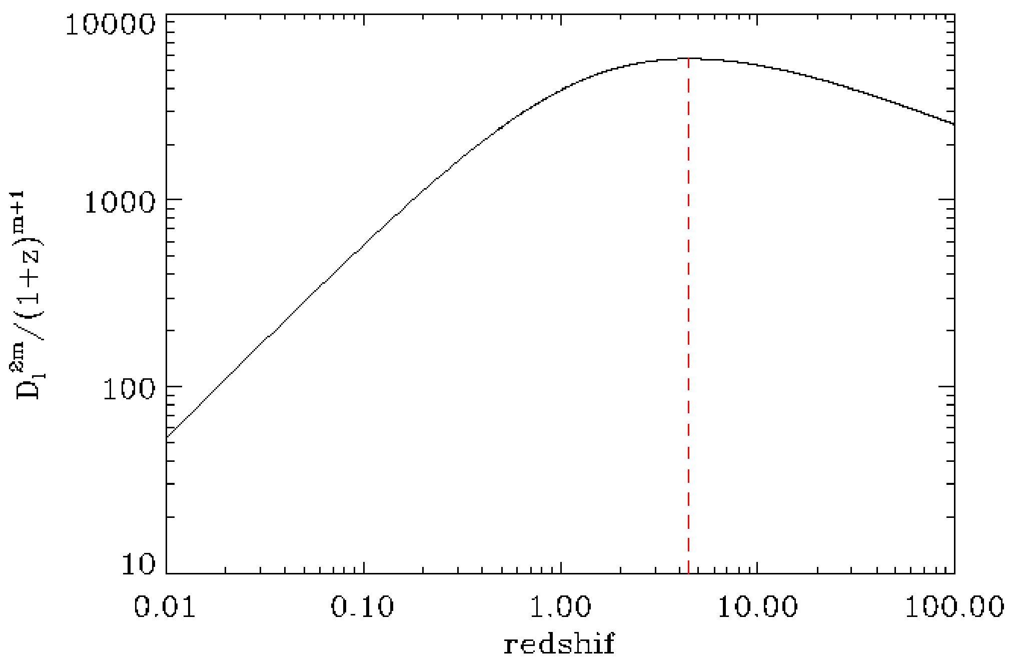
GRBs WITHOUT redshift (thousands)

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

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

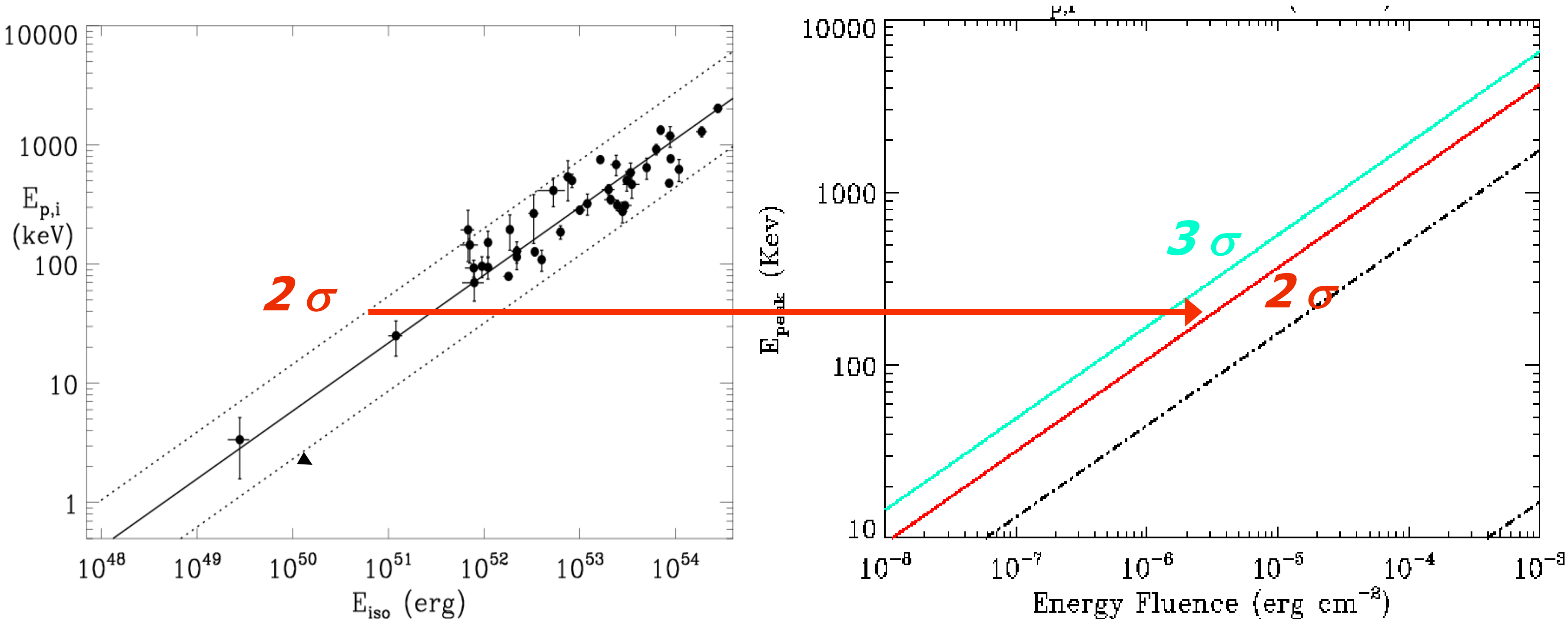
- the fit of the updated Ep,i – Eiso GRB sample with the maximum –likelihood method accounting for extrinsic variance provides a=0.53, k= 102, σ = 0.19

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



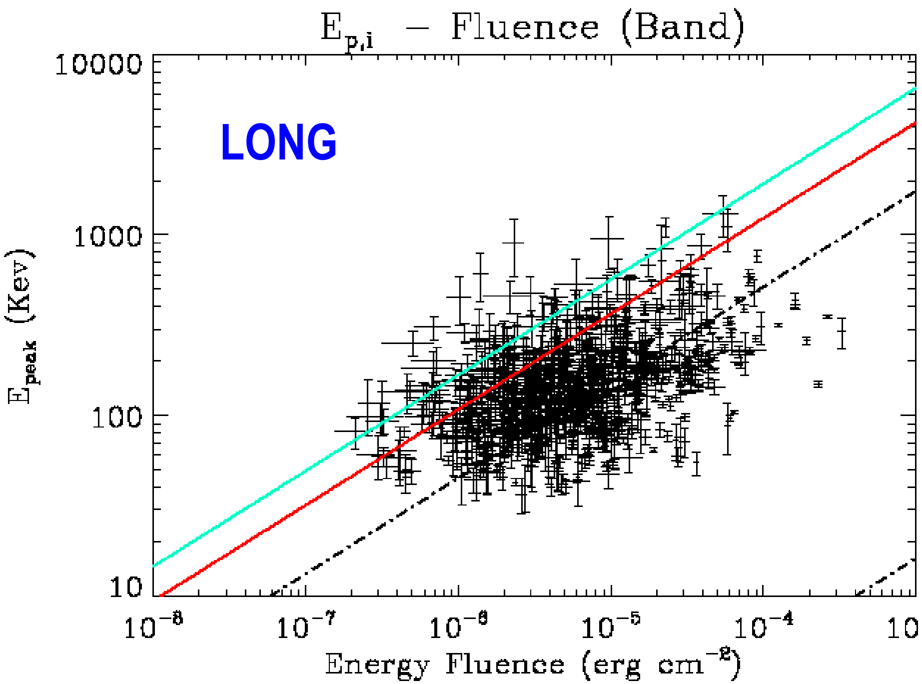
Intrinsic (cosm. Rest-frame) plane

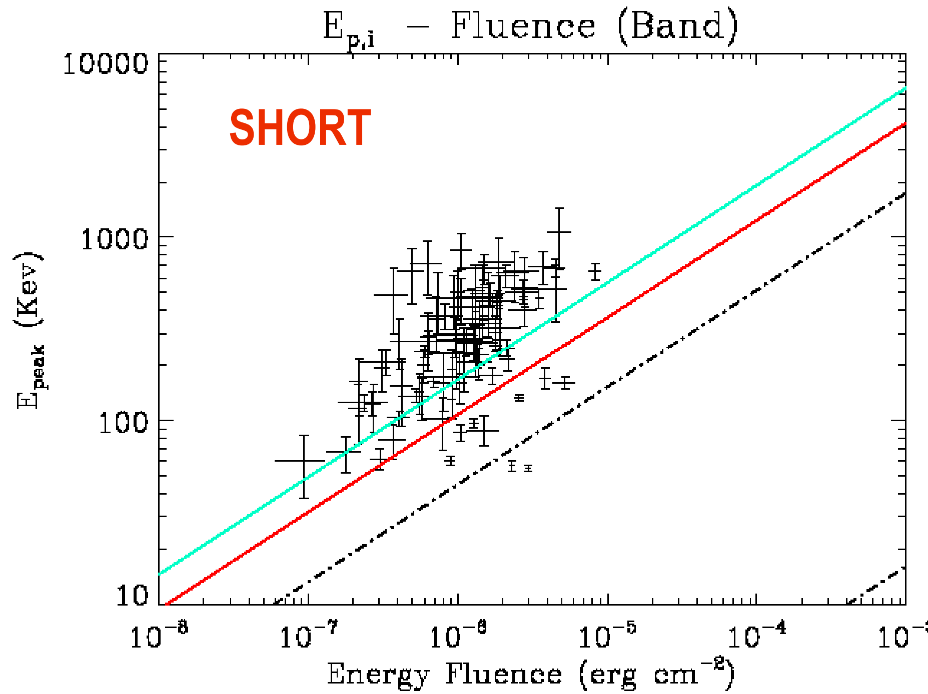
Observer's plane



- ❑ Amati, Dichiara et al. (2012, in prep.): consider fluences and spectra from the Goldstein et al. (2010) BATSE complete spectral catalog (on line data)

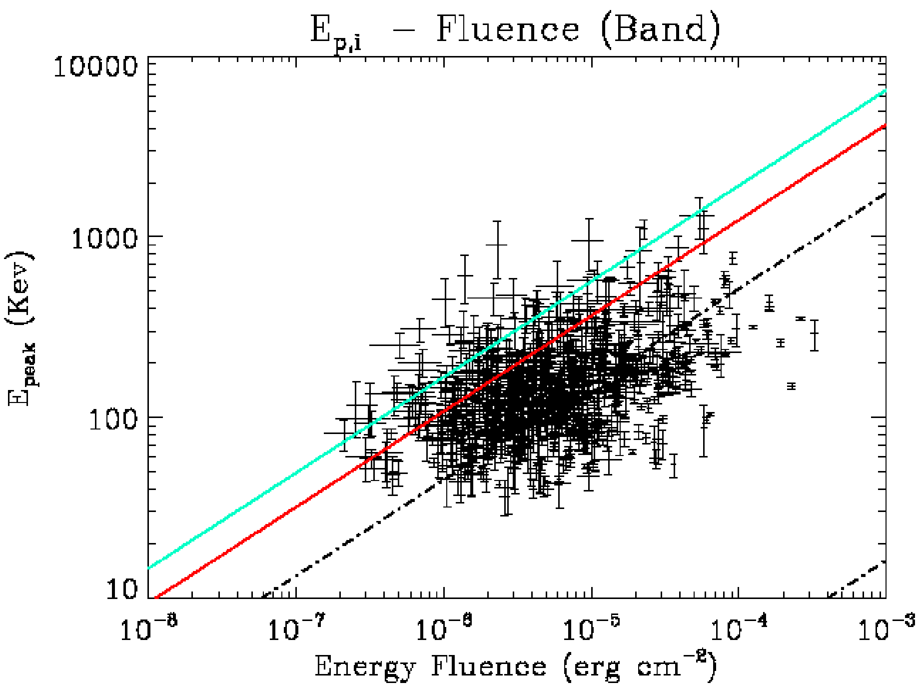
- ❑ considered long (777) and short (89) GRBs with fit with the Band-law and uncertainties on Ep and fluence < 40%



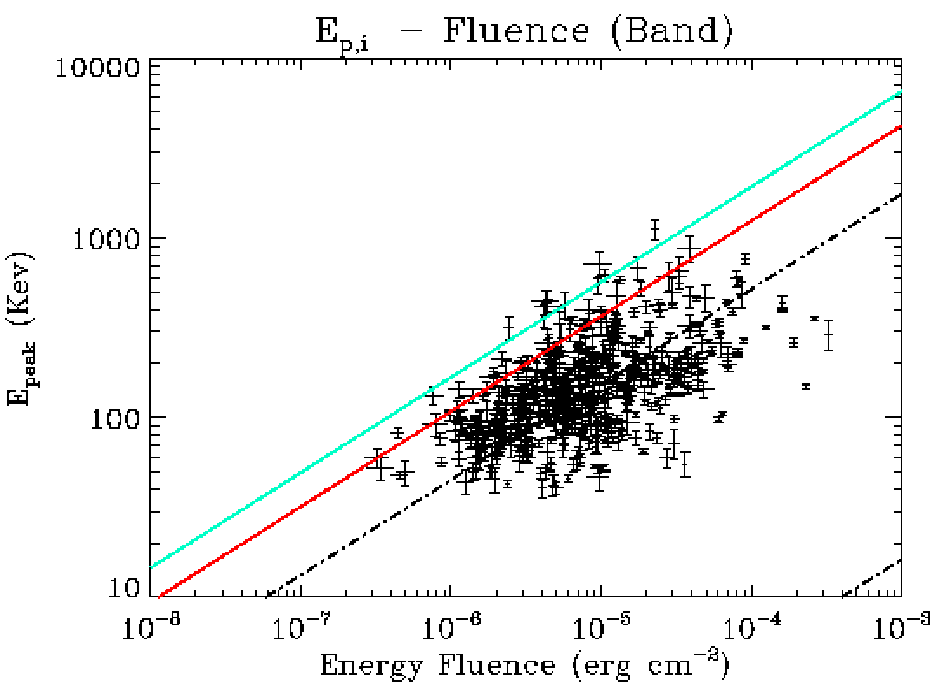


➢ **most long GRBs are potentially consistent with the Ep.i – Eiso correlation, most short GRBs are not**

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



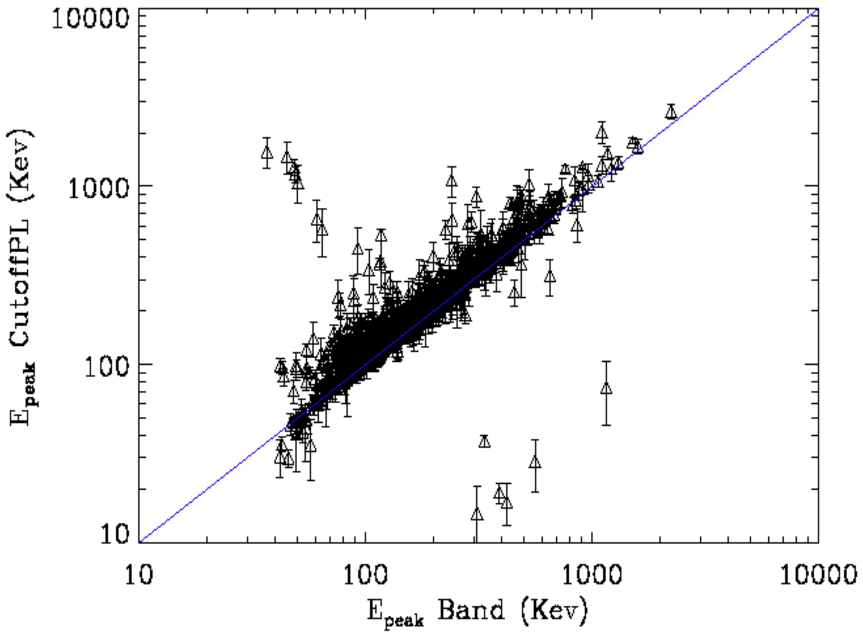
LONG, 40% unc.

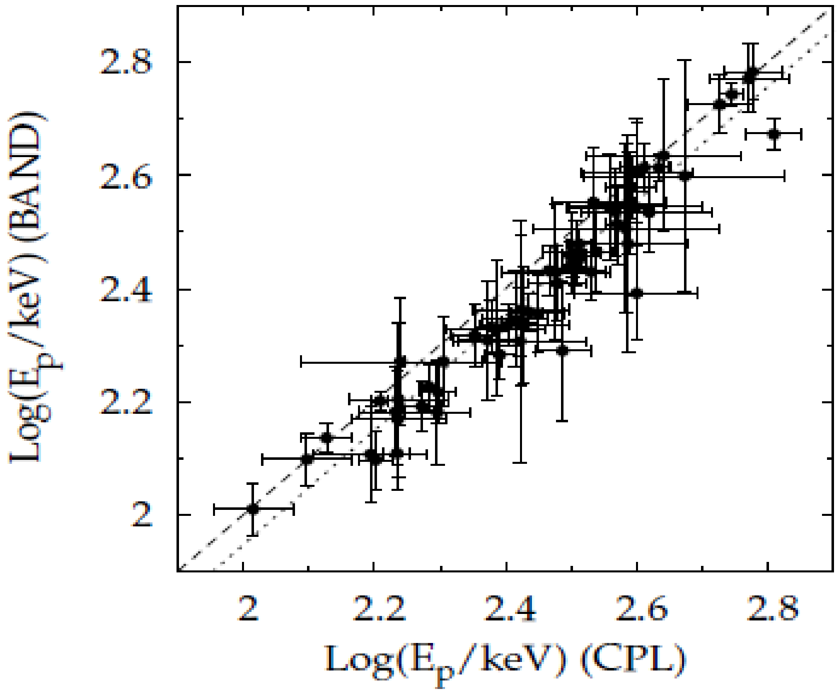


LONG, 20% unc.

- in addition to the large uncertainties on Ep and fluences, biases in the estimates of Ep and fluence of weak hard events have also to be taken into account:

a) fits with cut-off power-law (COMP) tend to overestimate Ep because of the too steep slope above Ep

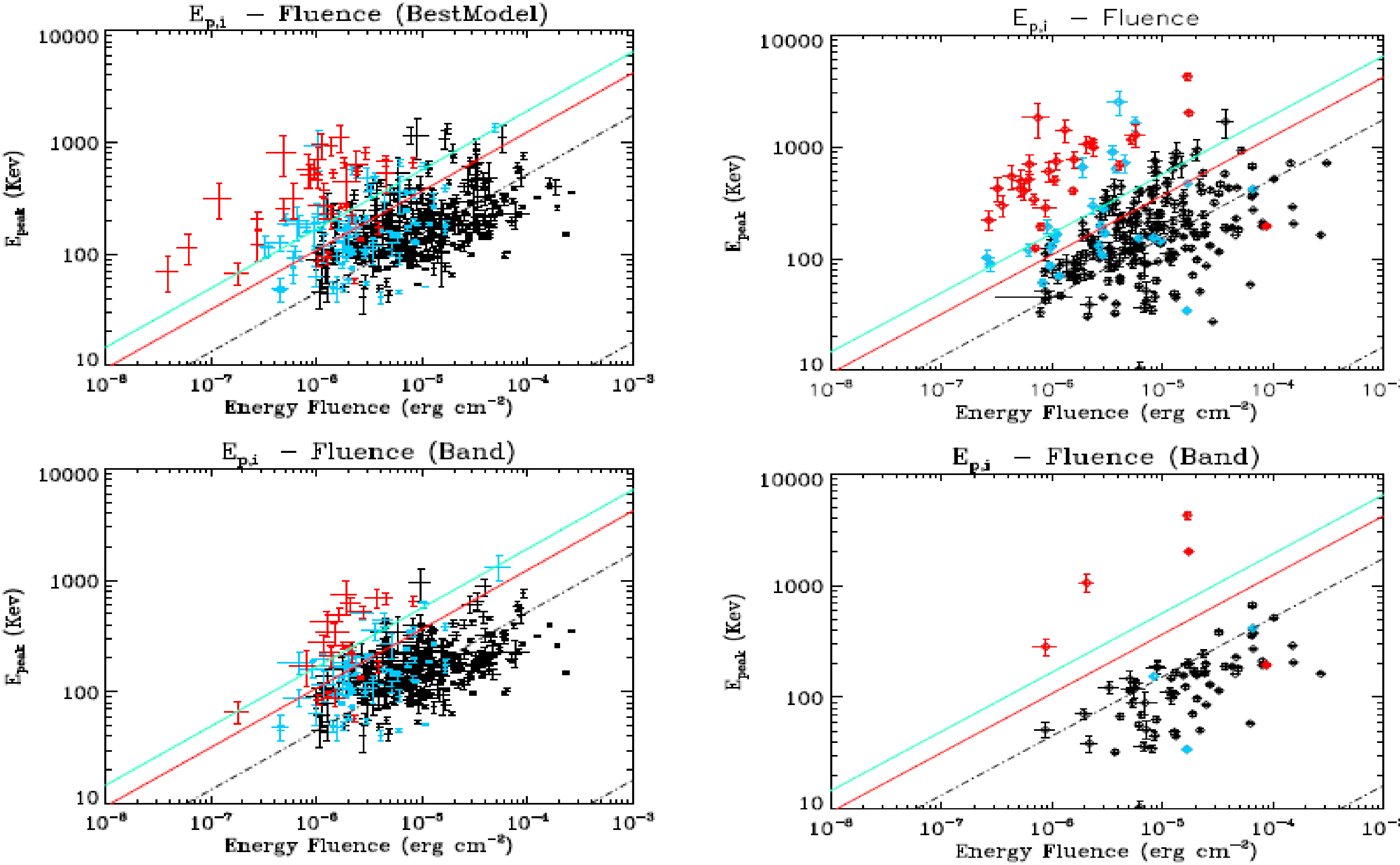




BATSE, sample of Goldstein et al. 2010

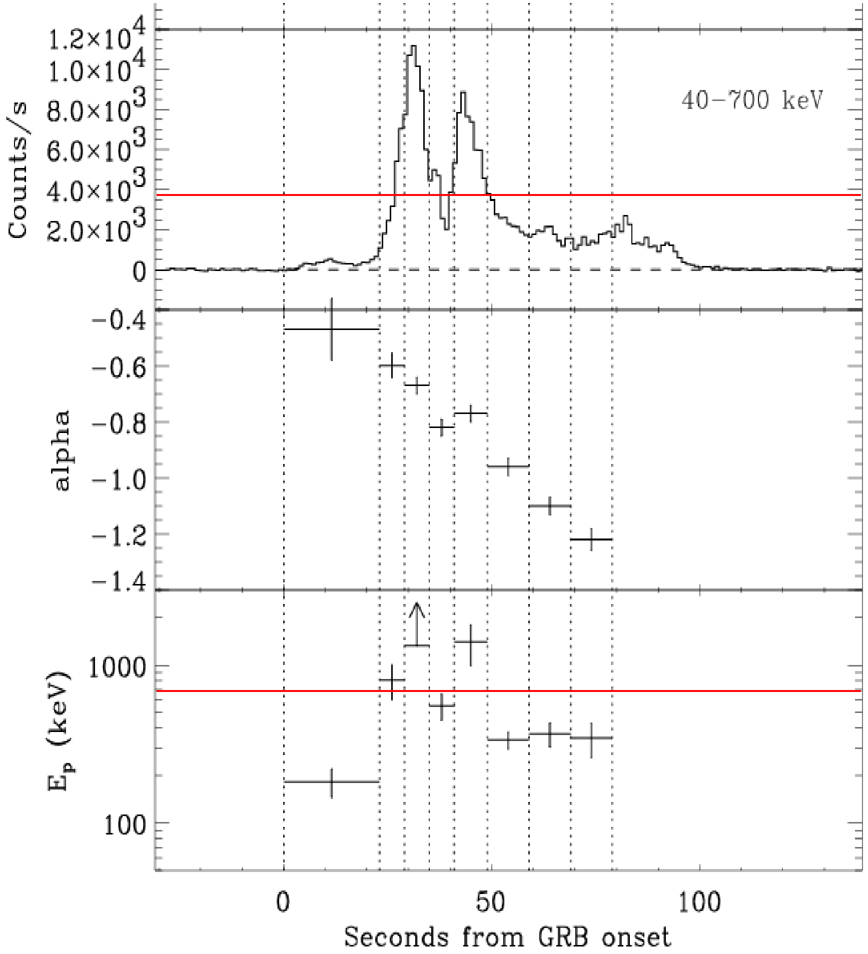
BeppoSAX/GRBM (Guidorzi et al. 2010)

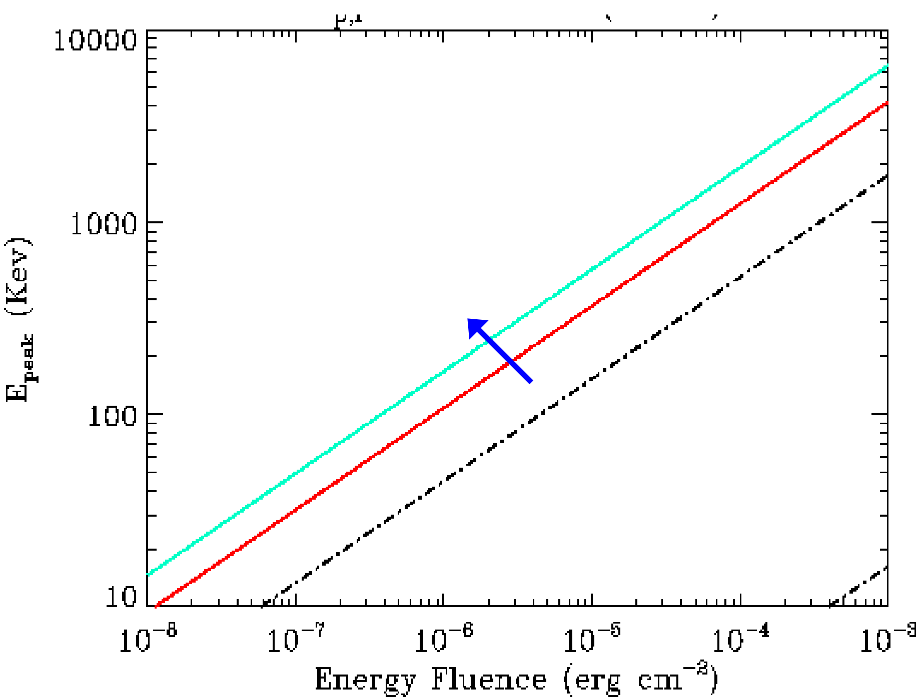
❑ ALL long BATSE and Fermi long GRBs with Ep and fluence derived form fit with Band function are potentially consistent with the correlation



BATSE (data from Goldstein+10) **Fermi (data from Nava+11)**

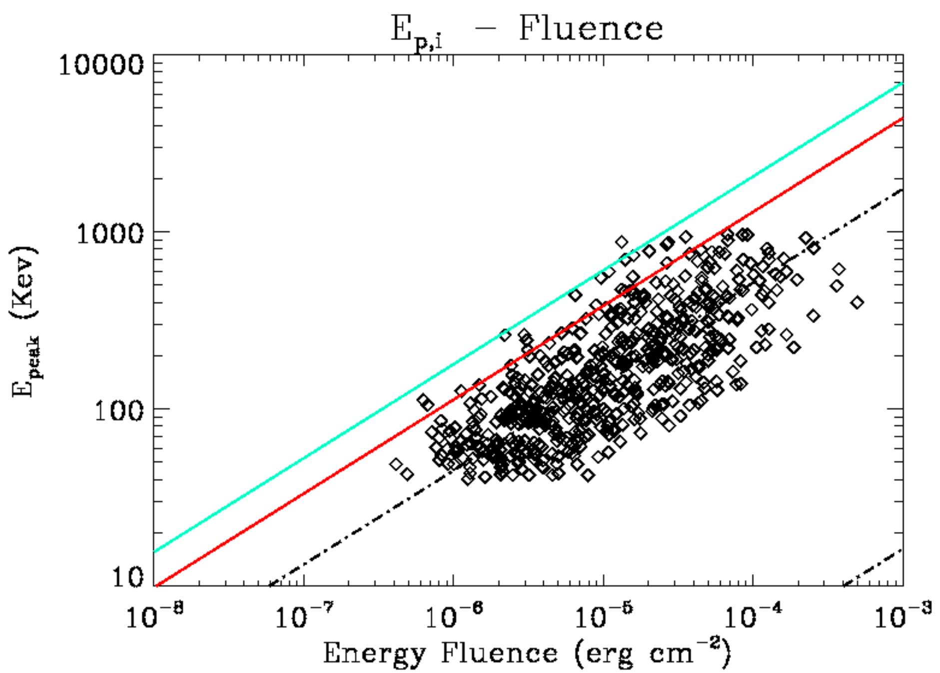
b) measure only the harder portion of the event: overestimate of Ep and underestimate of the fluence

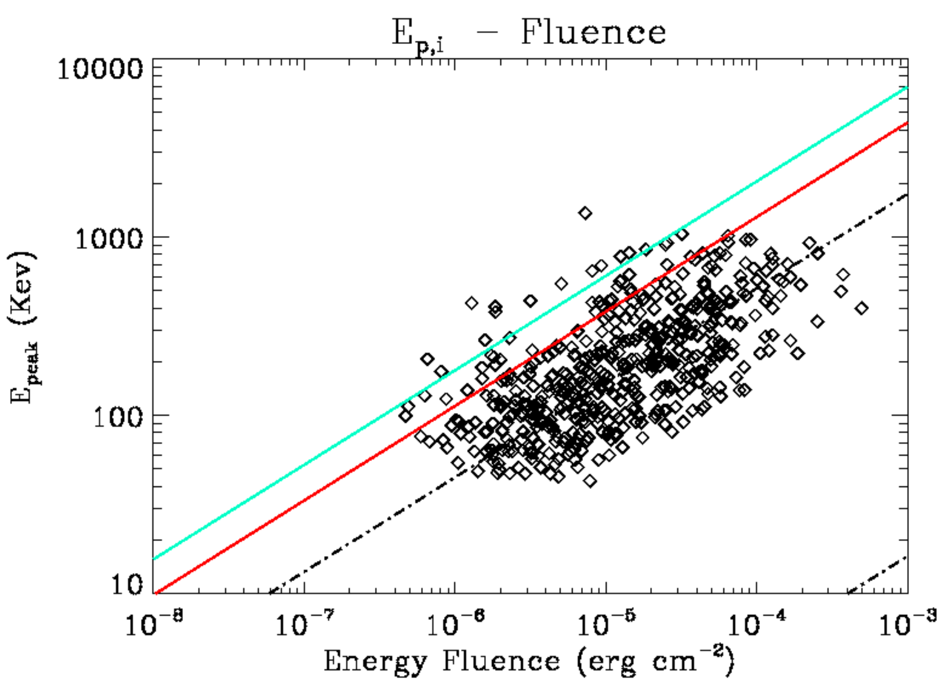




- Amati, Dichiara et al. (2011, in prep.): MC simulations assuming the existence and the measured parameters of the Ep,i – Eiso correlation and accounting for the observed distributions (Eiso, z, Eiso vs. z) and BATSE instrumental sensitivity as a function of Ep (Band 2003-2009)

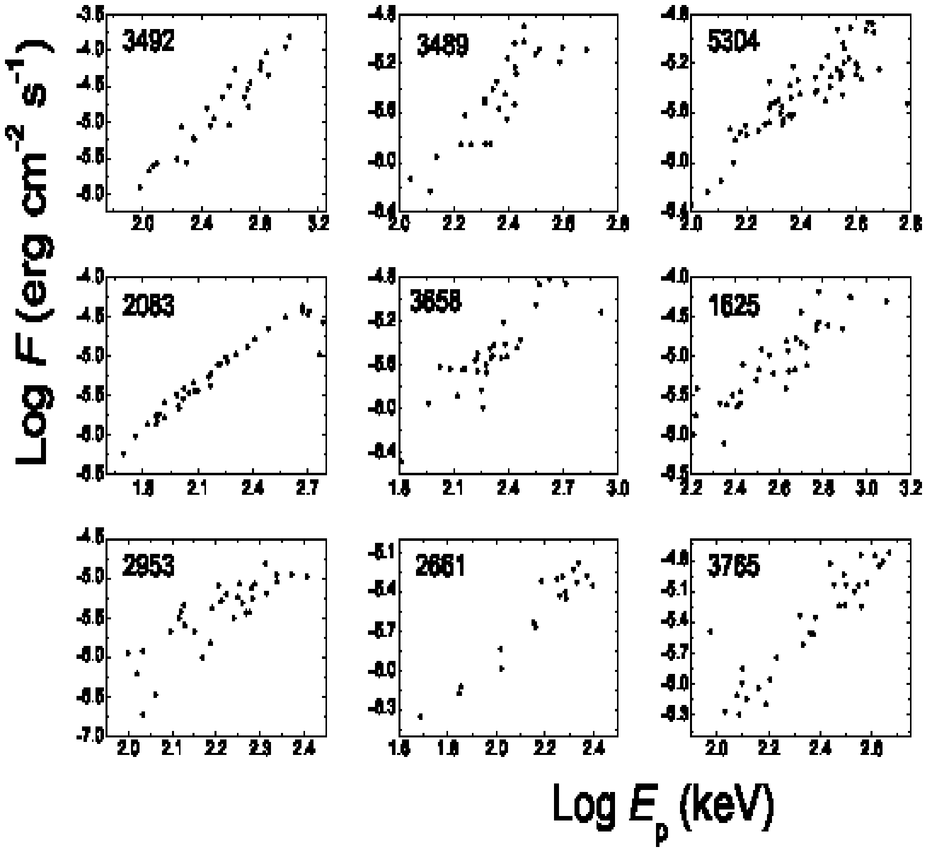
- When accounting for spectral evolution, i.e. Ep = f(Flux), **the small fraction of "outliers" in the Ep,obs – Fluence plane is reproduced**

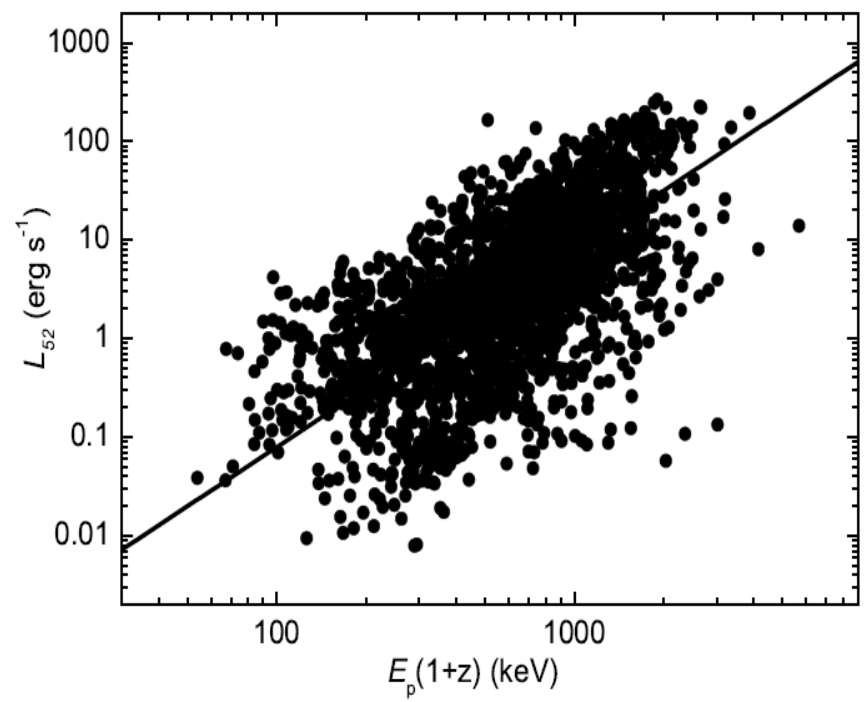




The Ep,i – intensity correlation within single GRBs

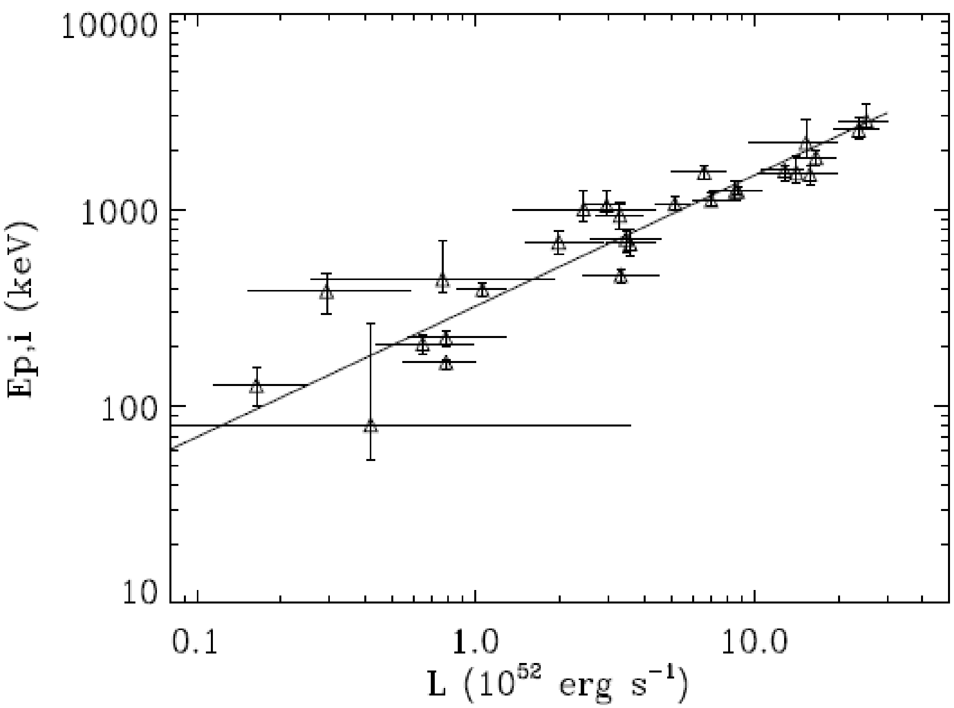
- Liang et al.2004: evidence for an Ep – Flux correlation within most BATSE GRBs and, based on pseudo-redshifts, possible existence of a univoque Ep,i(t) – Liso(t) correlation



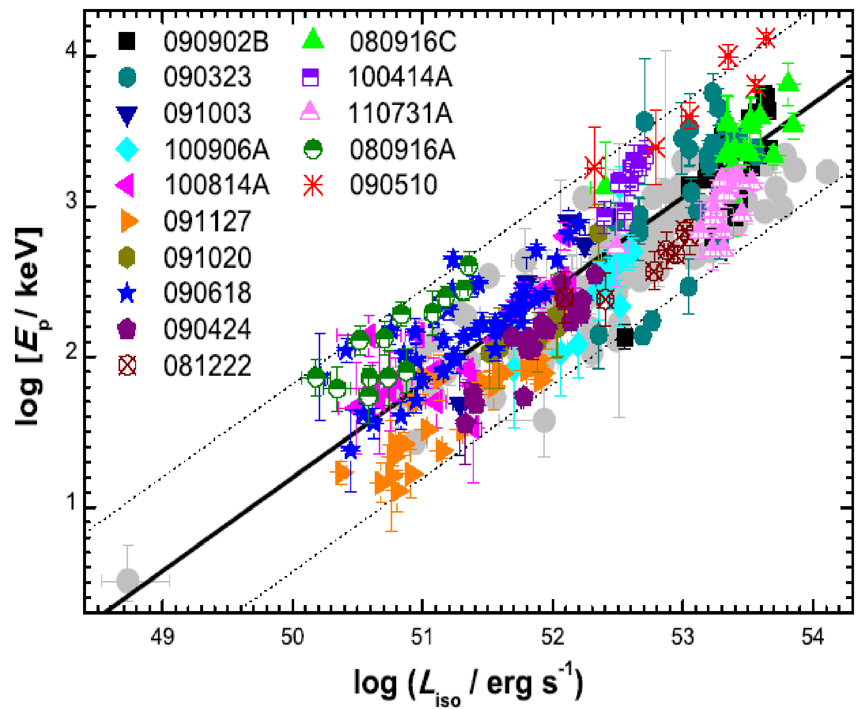


Liang et al., ApJ, 2004

➢ 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)

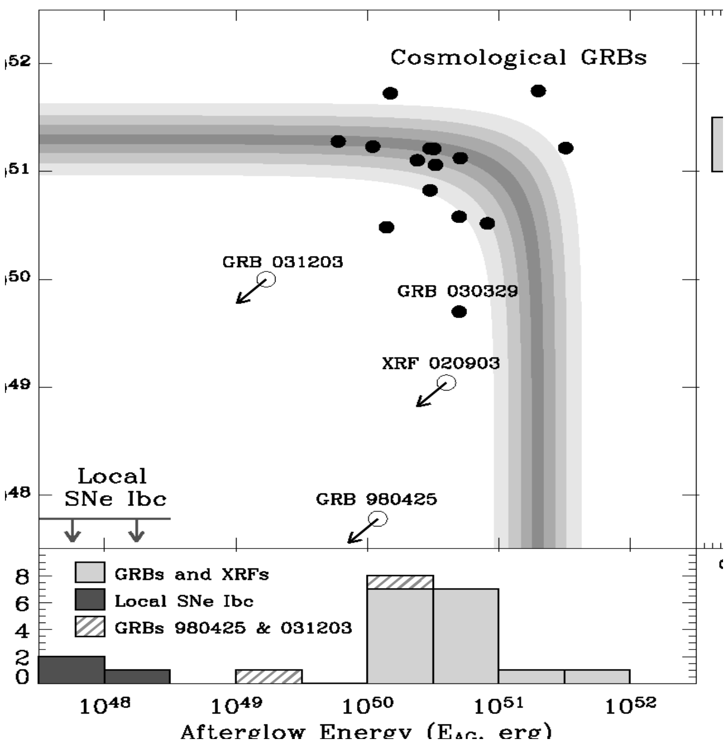


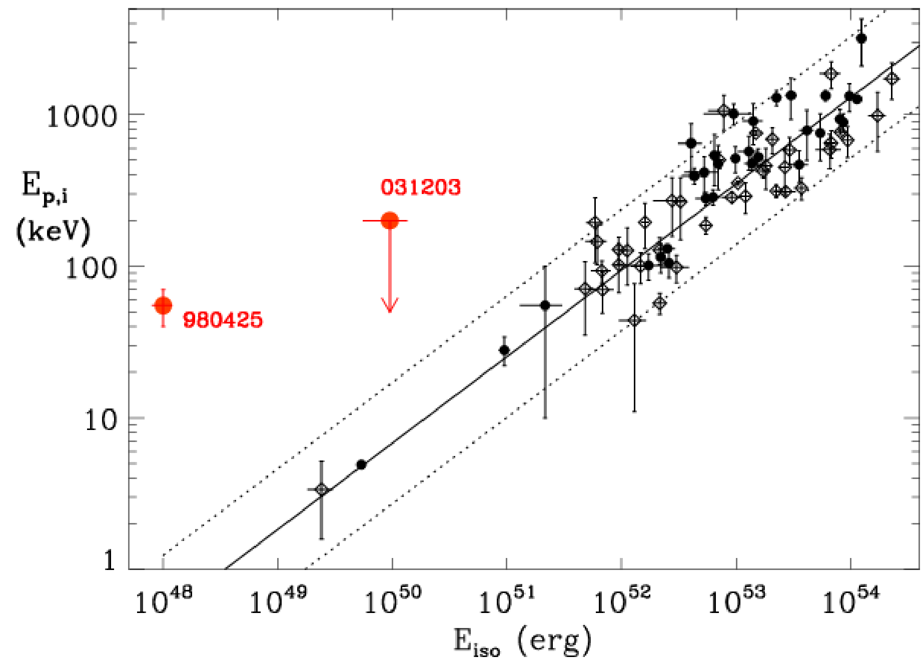
Fermi (e.g., Li et al. , ApJ, 2012)

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)

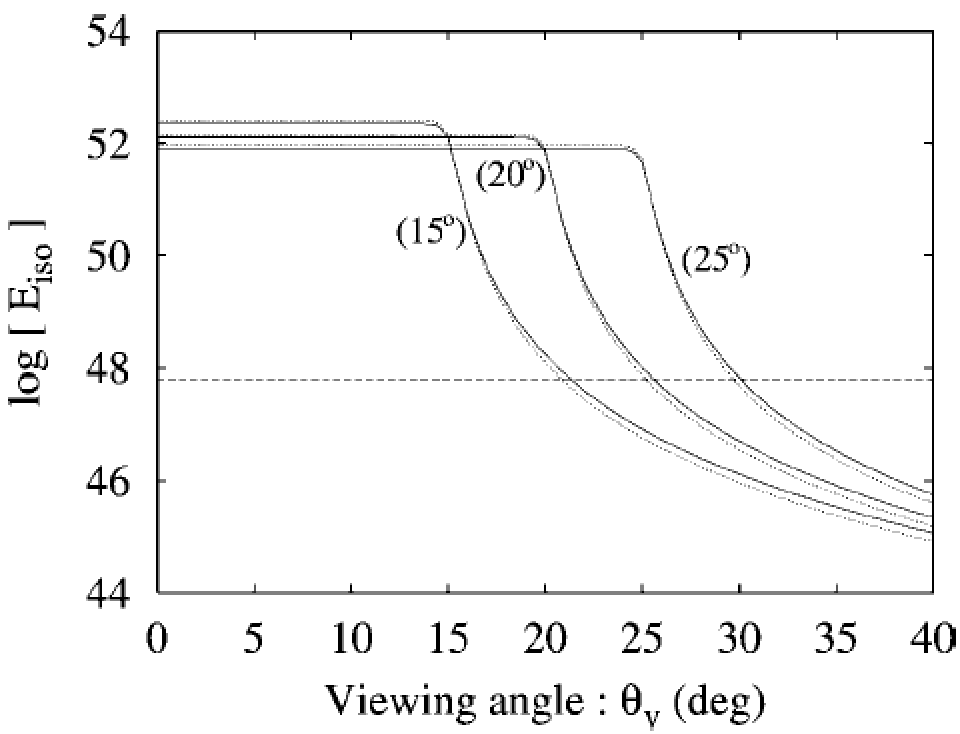
❑ GRB031203: the most similar case to GRB980425/SN1998bw: very close (z = 0.105), SN2003lw, sub-energetic



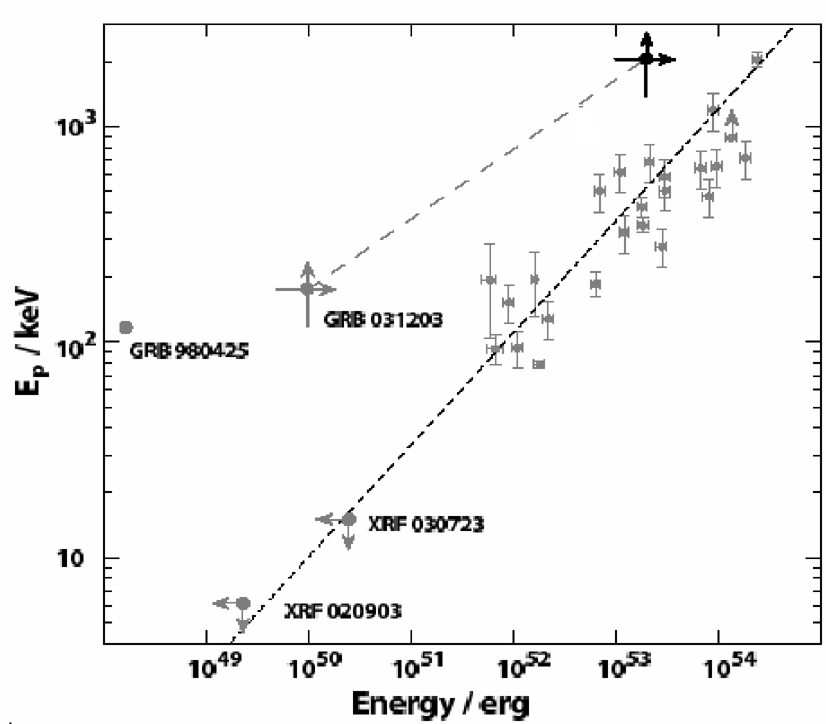


- the most common explanations for the (apparent ?) sub-energetic nature of GRB980425 and GRB031203 and their violation of the Ep,i – Eiso correlation assume that they are NORMAL events seen very off-axis (e.g. Yamazaki et al. 2003, Ramirez-Ruiz et al. 2005)
- $\delta=[\gamma(1 - \beta\cos(\theta v -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

  $\alpha=1\div2.3$ -> $\Delta Eiso \propto \delta^{(2 \div 3.3)}$



Yamazaki et al., ApJ, 2003

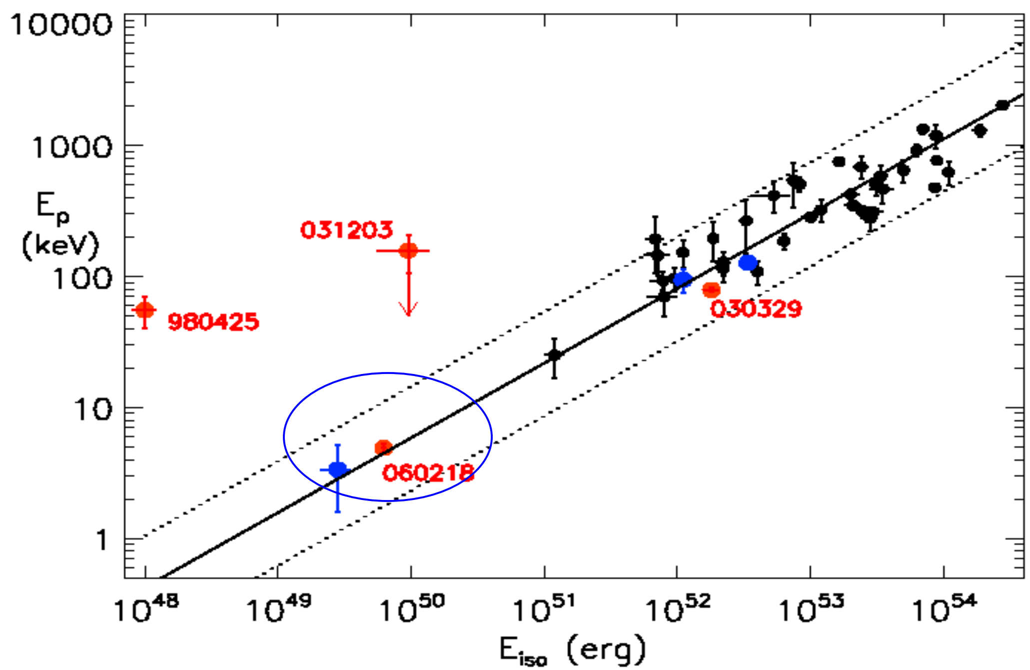


Ramirez-Ruiz et al., ApJ, 2004

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

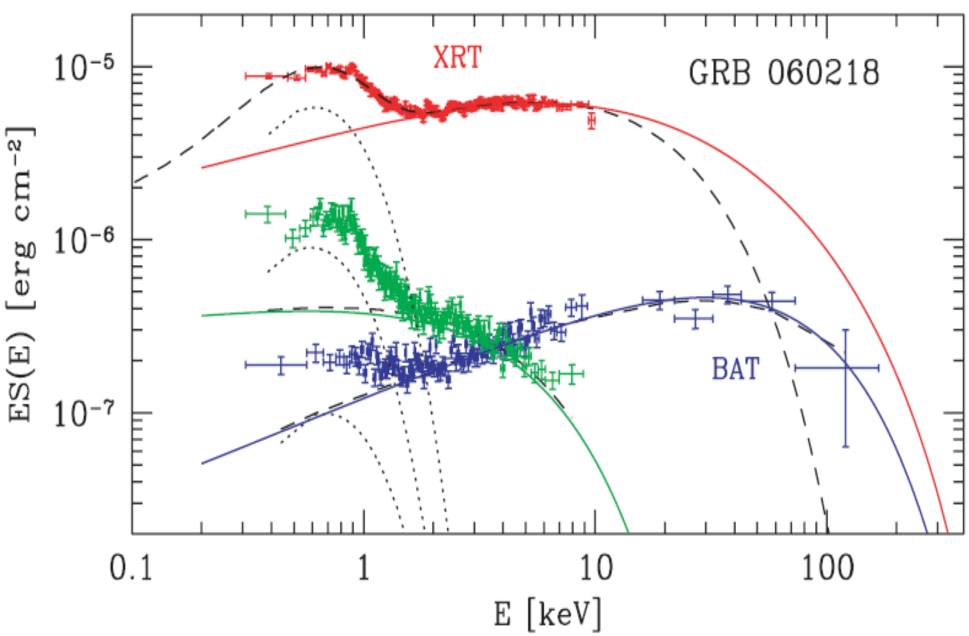


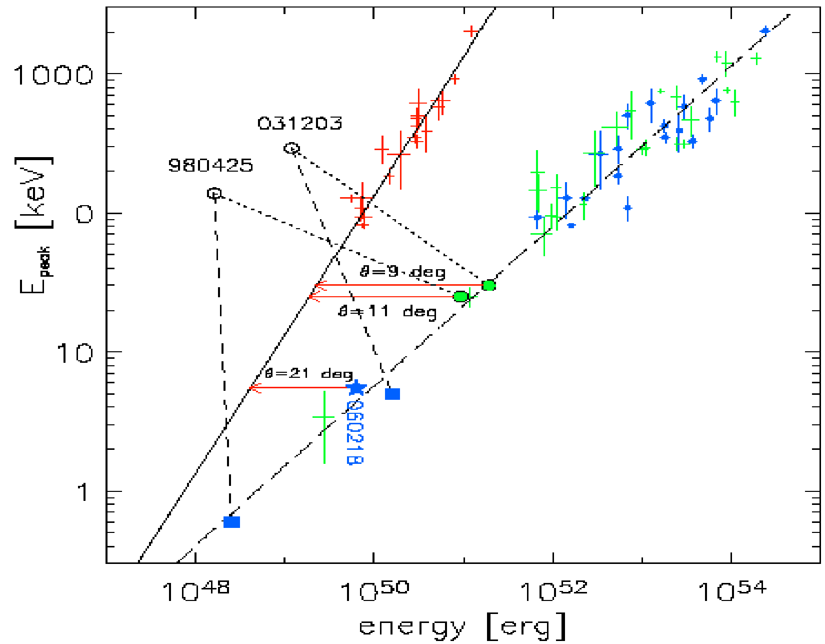
Amati et al., 2007

- GRB060218 was a very long event (~3000 s) and without XRT 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

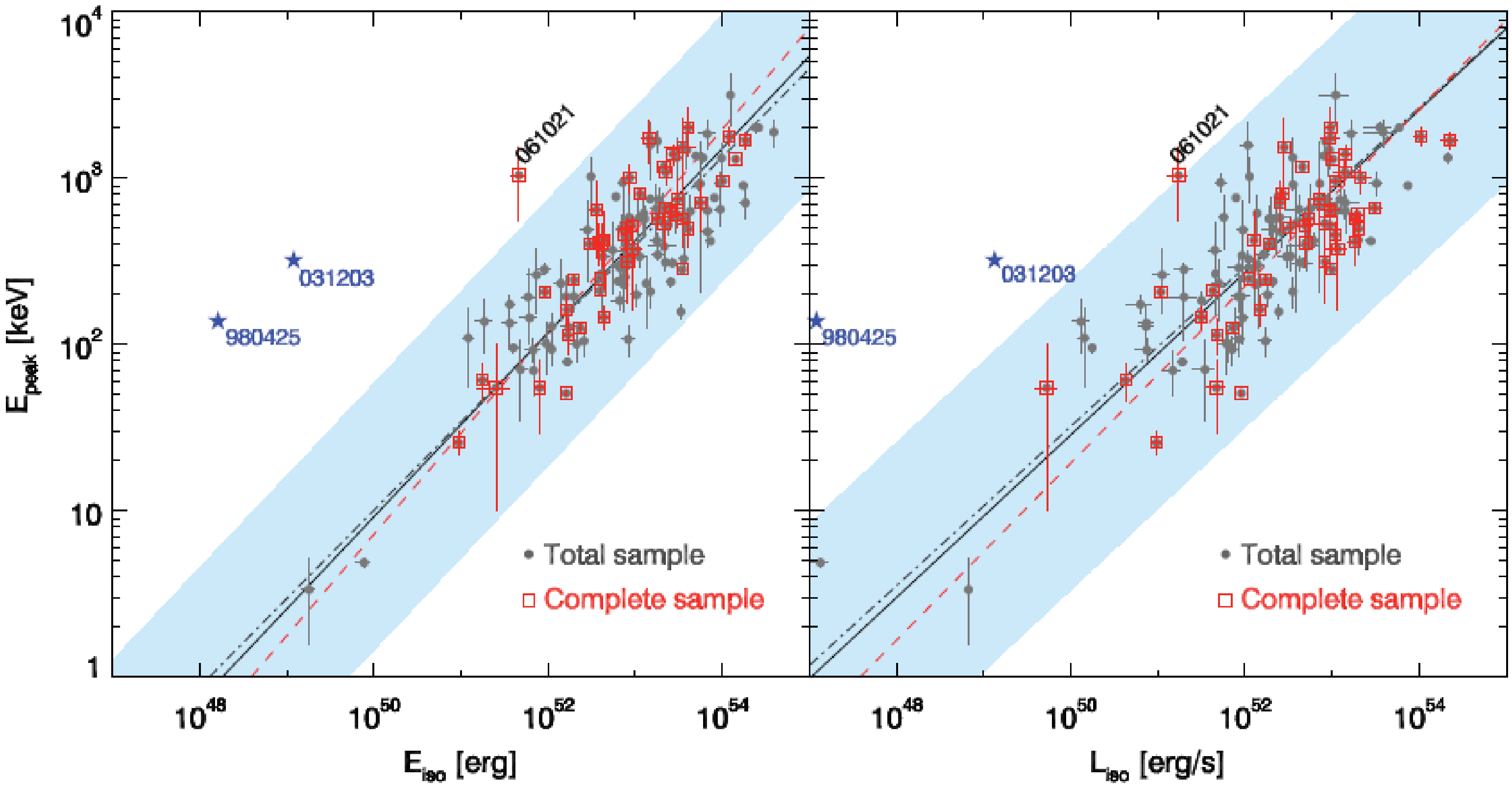
- sub-energetic GRB consistent with the correlation; apparent outliers(s) GRB 980425 (GRB 031203) could be due to viewing angle or instrumental effect





❑ 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"

Conclusions

- The Ep,i – intensity (Eiso, Liso, Lp,iso, …) correlation is one of the most intriguing properties of GRBs, with relevant implications for prompt emission physics and geometry, identification and understanding of different classes of GRBs, use of GRBs for cosmological parameters.

- Both the analyses of GRBs with and without measured redshift, including Swift and Fermi data, show that there is no firm evidence of significant selection / instrumental effects.

- The existence of the Ep,i(t) – Liso(t) correlation within single GRBs is a further strong evidence of the physical origin of the Ep,i – intensity correlation found with time-integrated(averaged) spectra.

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- The simulatenous operation of Swift, Fermi/GBM, Konus-WIND and, in particular of future GRB experiments (e.g., SVOM) will increase the number of GRBs with redshift and accurate mesurements Ep, fluence, fp, Eiso, Lp,thus allowing further testing Ep-intensity correlations