On the reliability of the $E_{p,i}$ – intensity correlation

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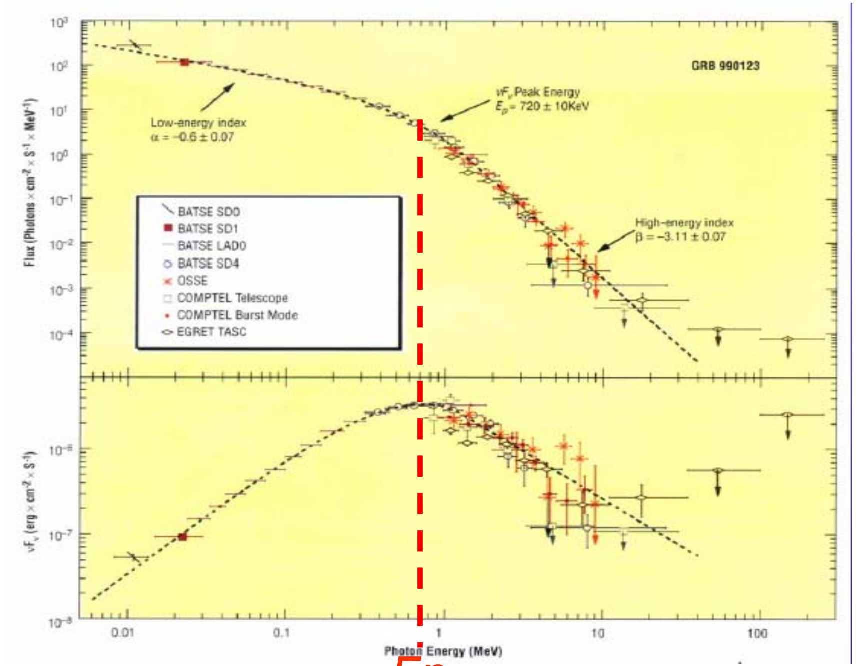
The Ep,i – Eiso correlation

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

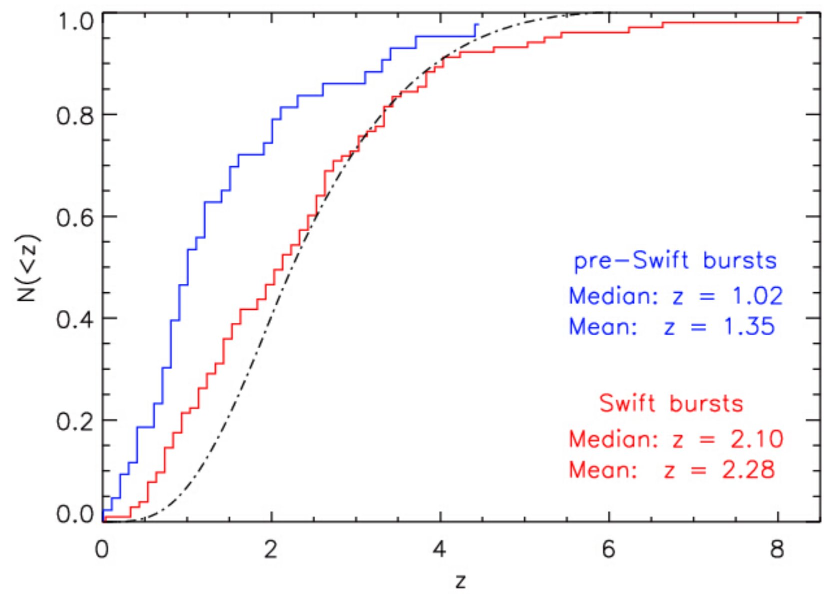
➢ $E_p = E_0 \times (2 + \alpha)$ = observed peak energy of the $\nu F\nu$ spectrum

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

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

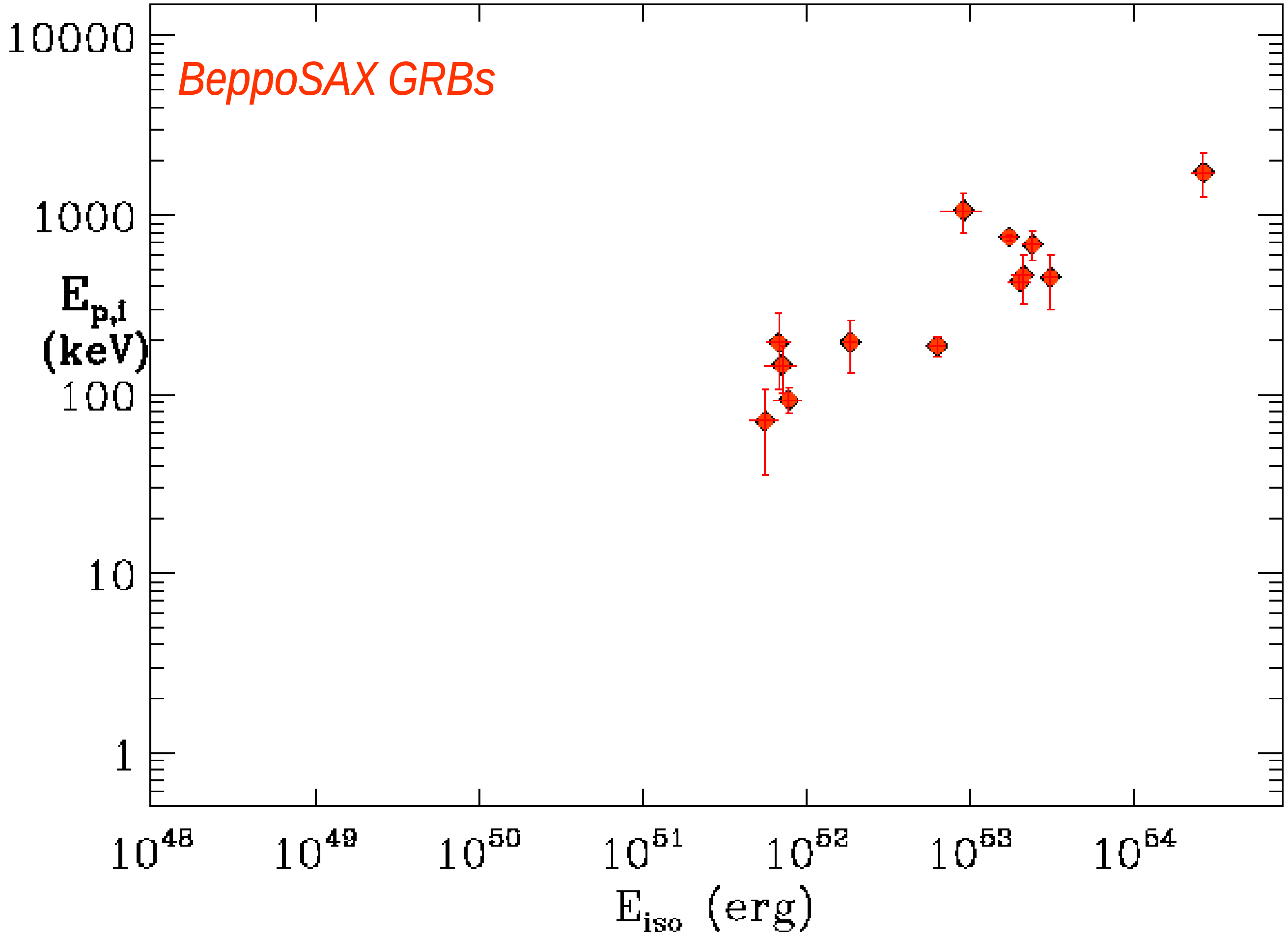


Ep



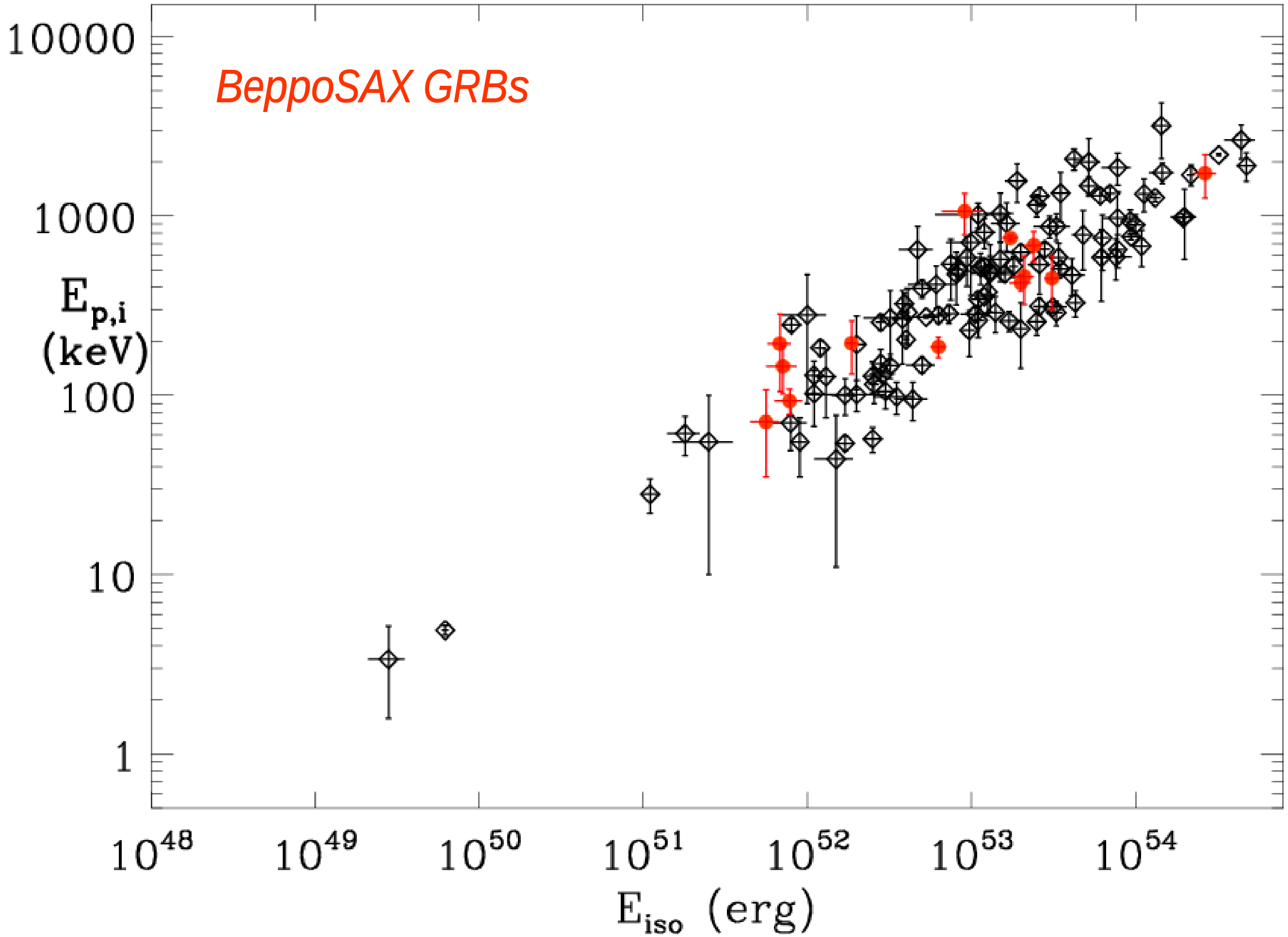
Jakobsson (2009)

➢ 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

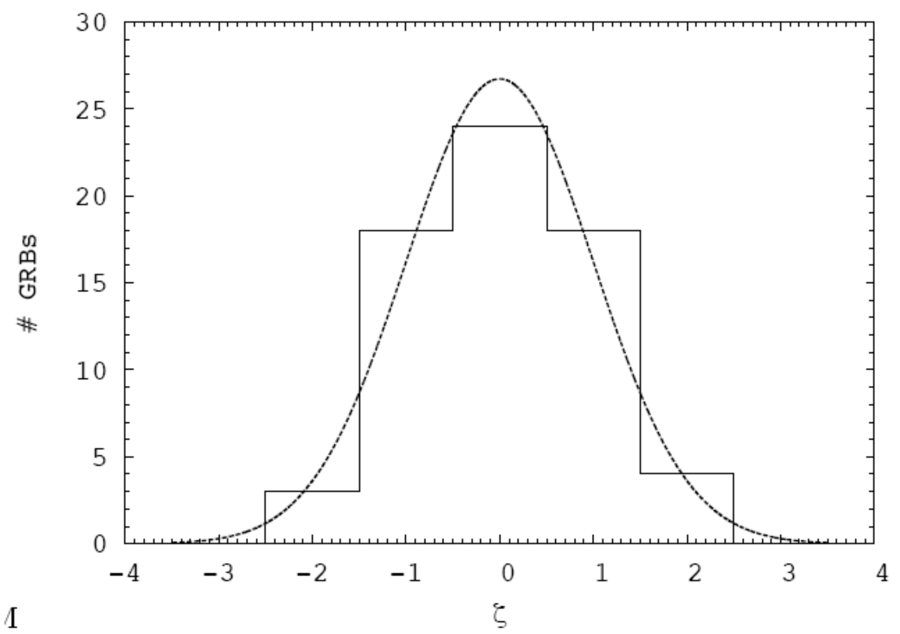


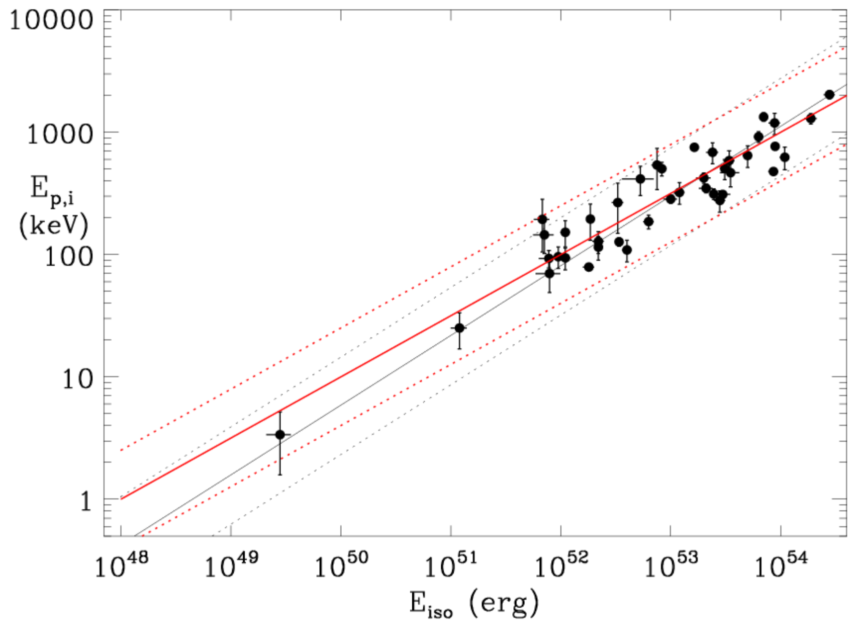
➢ strong correlation but significant dispersion of the data around the best-fit power-law; the distribution of the residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

➢ 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



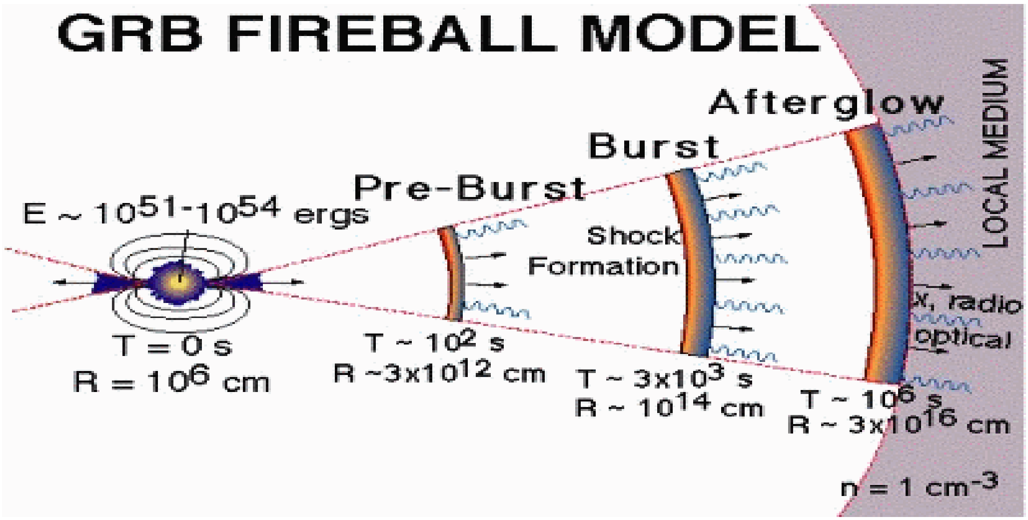


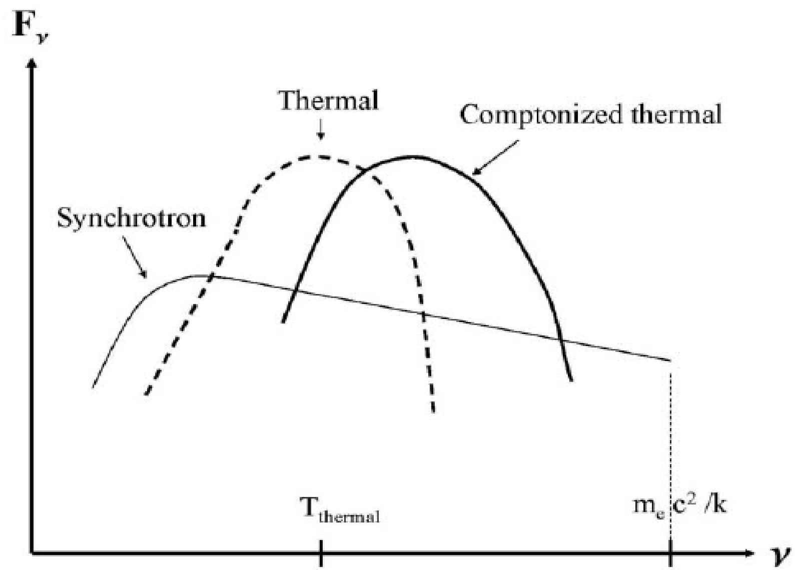
➢ implications and uses: prompt emission physics

❑ 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)

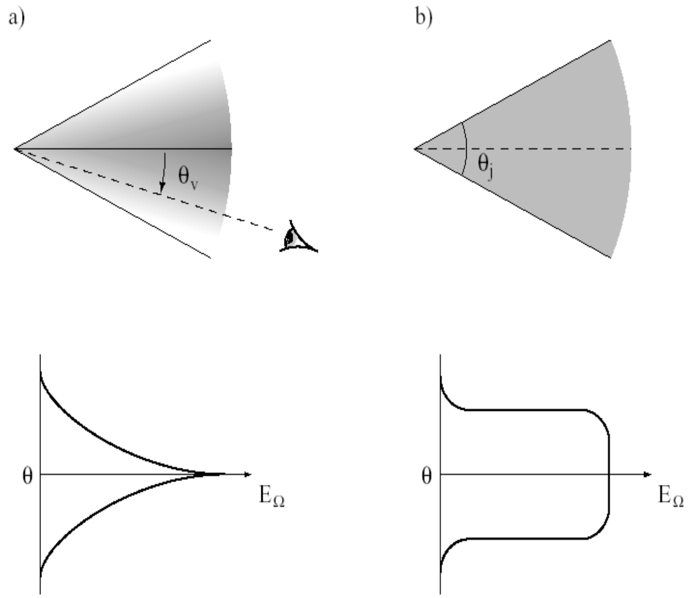


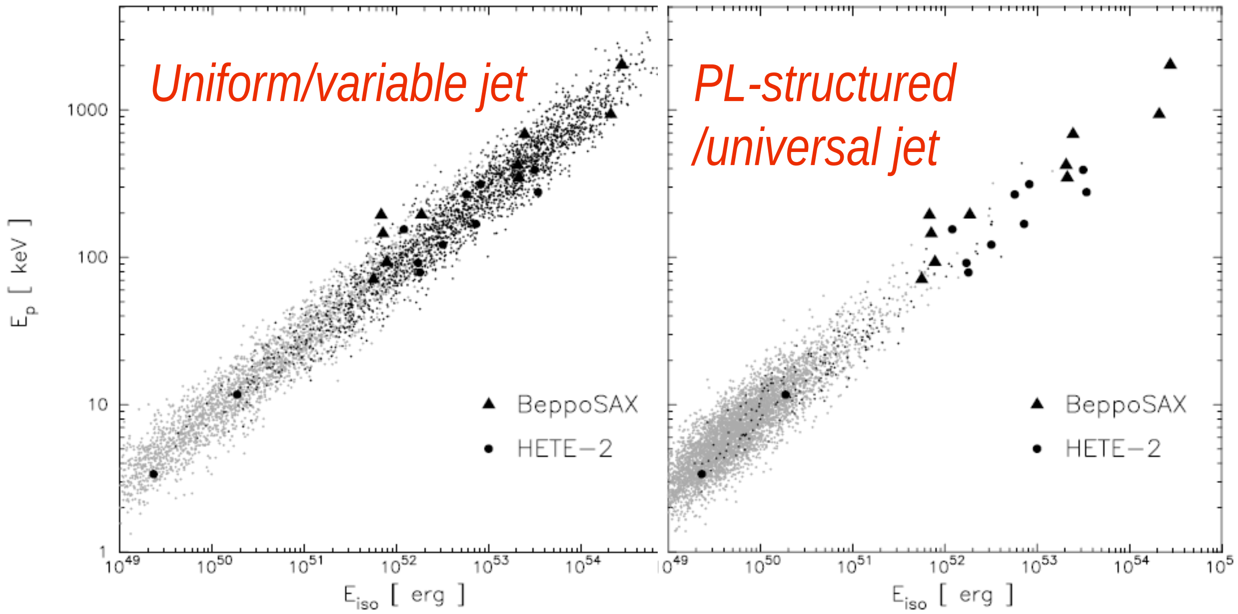


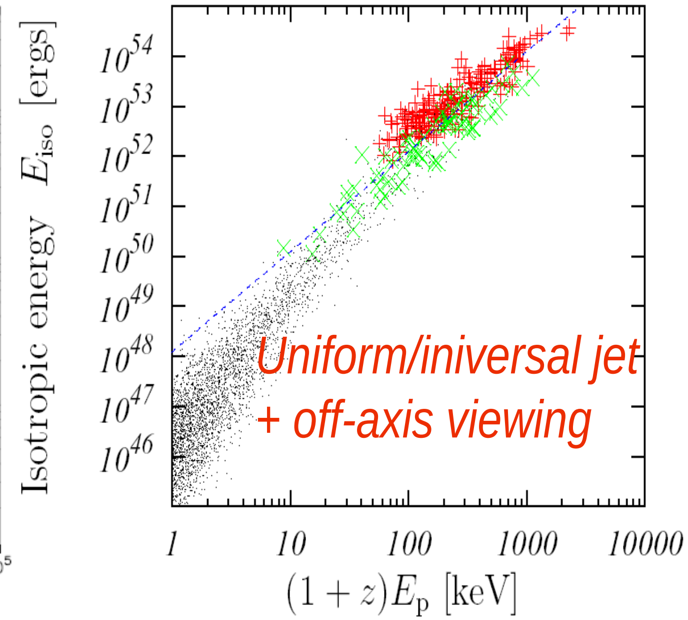
➢ implications and uses: jet structure and viewing angle effects

❑ 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.)



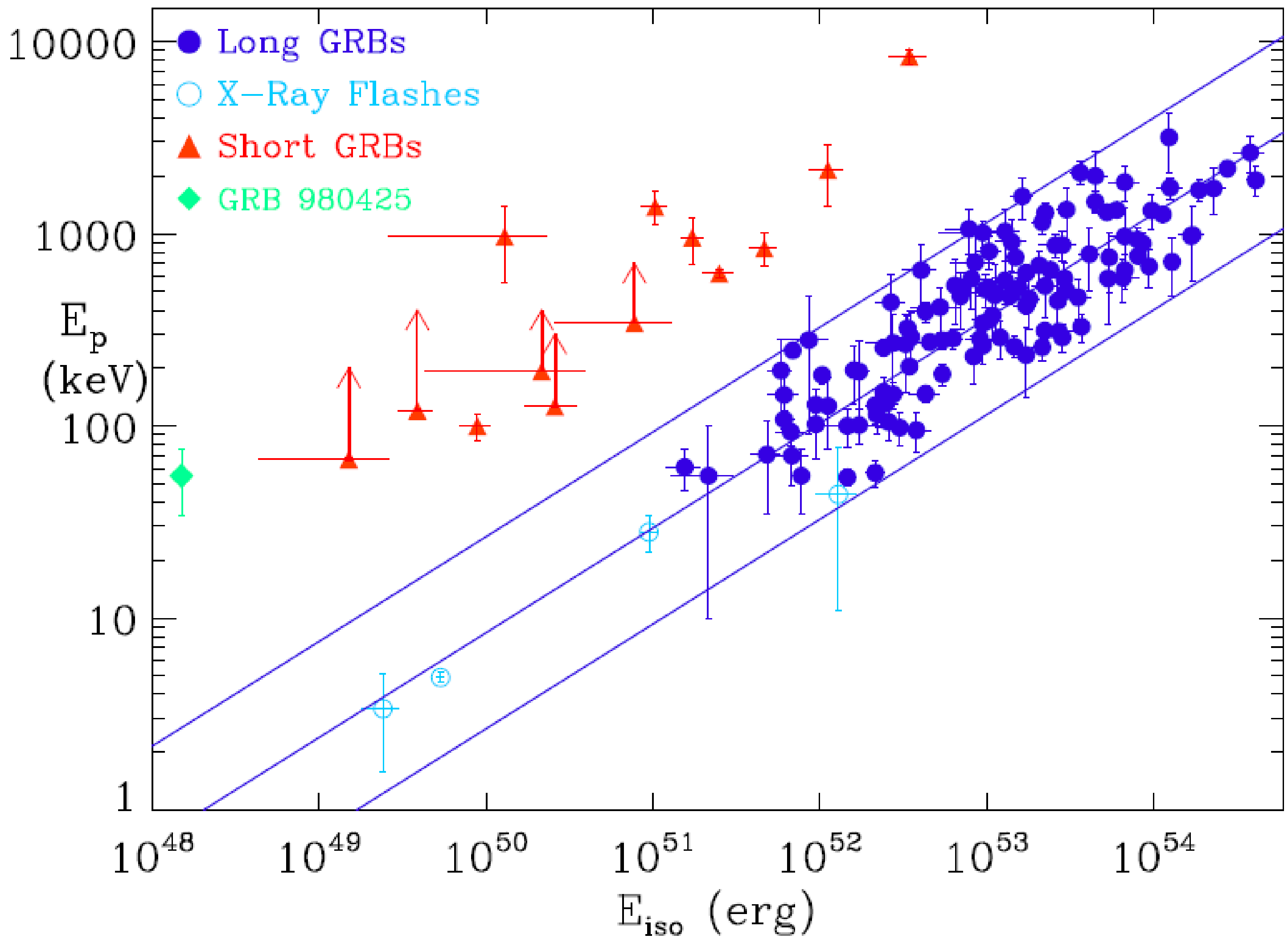




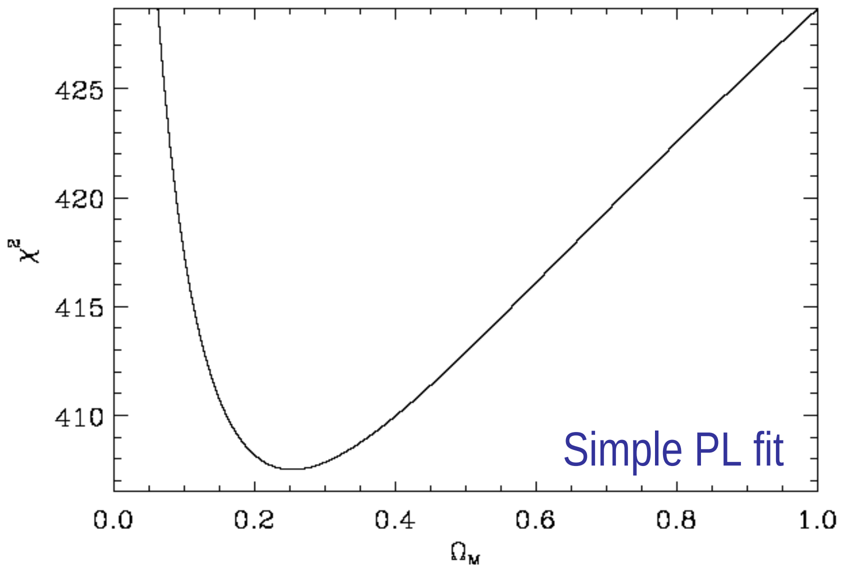
Lamb et al. 2005

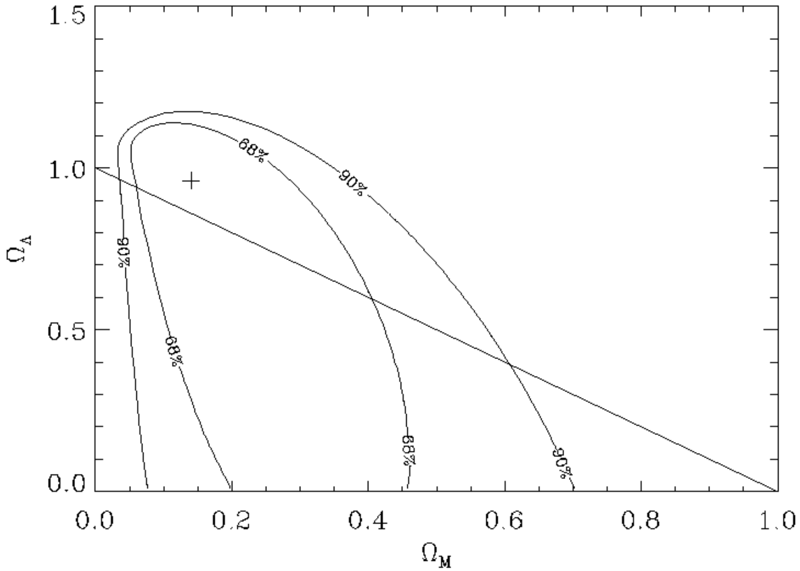
Yamazaki et al. 2004

➢ implications and uses: identifying and understaning different classes of GRBs

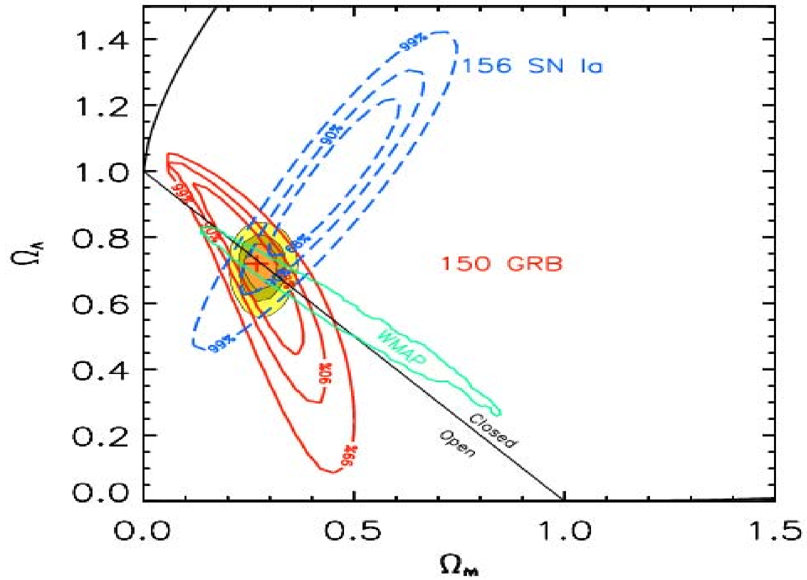


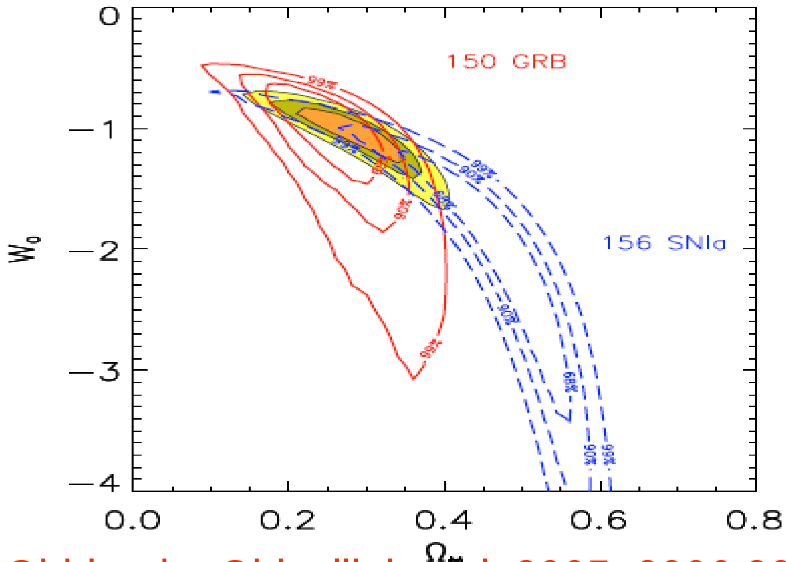
➢ implications and uses: GRB cosmology





Amati et al. 2008, 2012



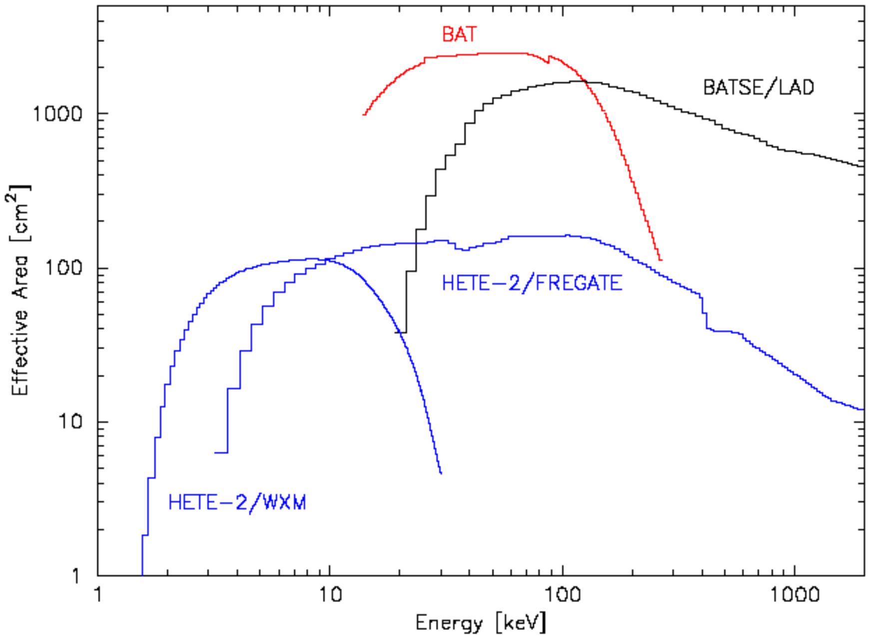


Ghirlanda, Ghisellini et al. 2005, 2006,2007

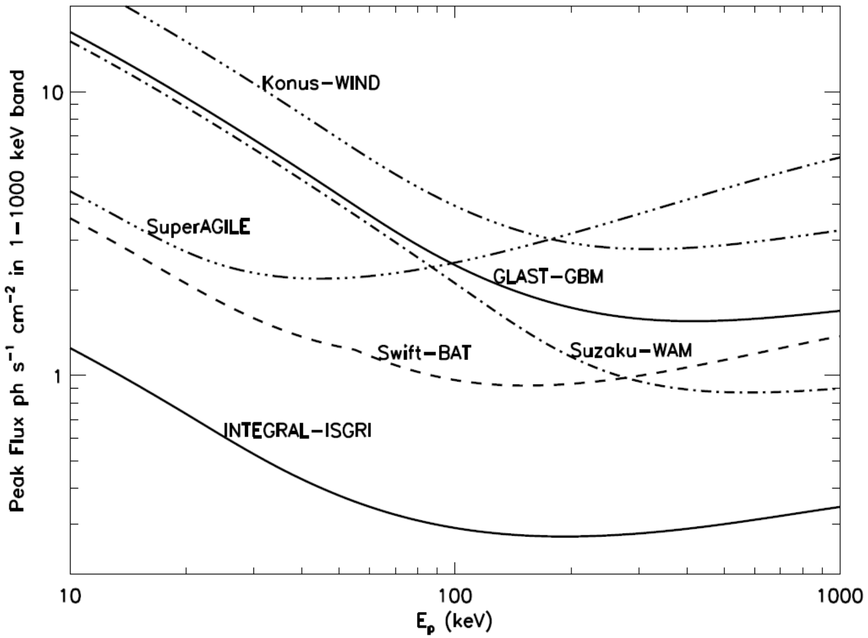
Instrumental and selection effects

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

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

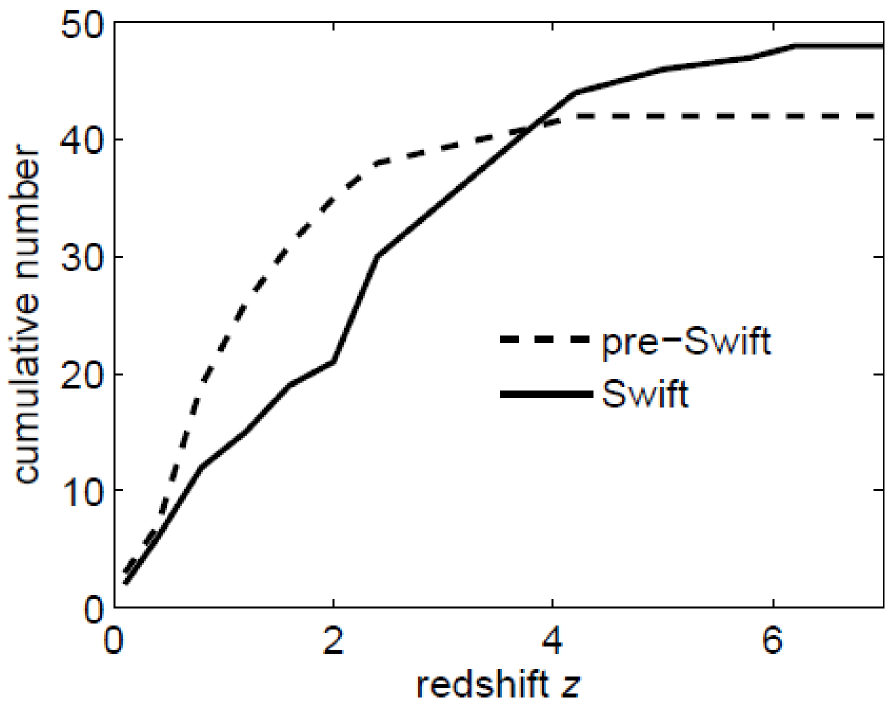


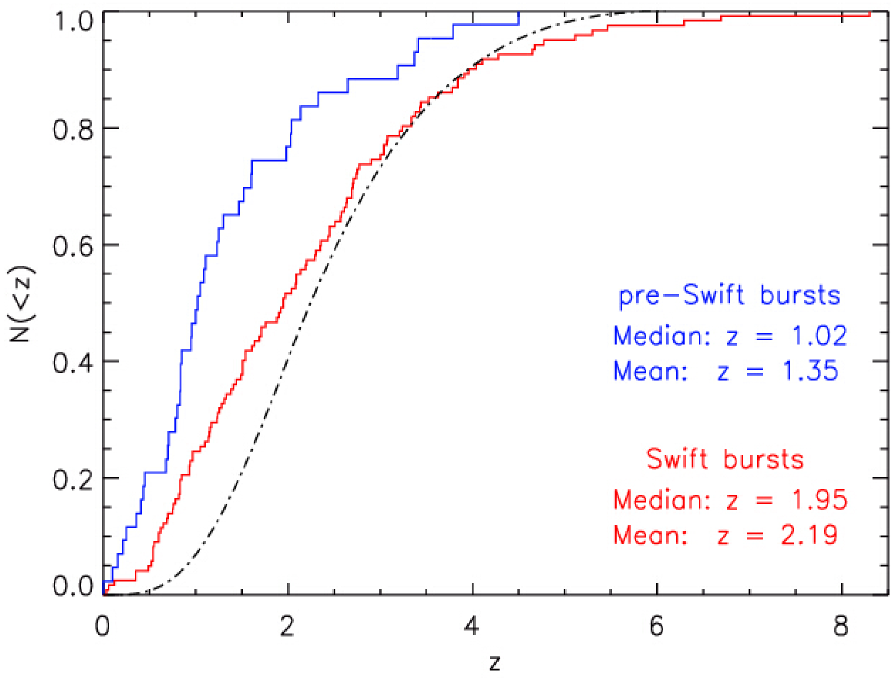
Sakamoto et al. 2011

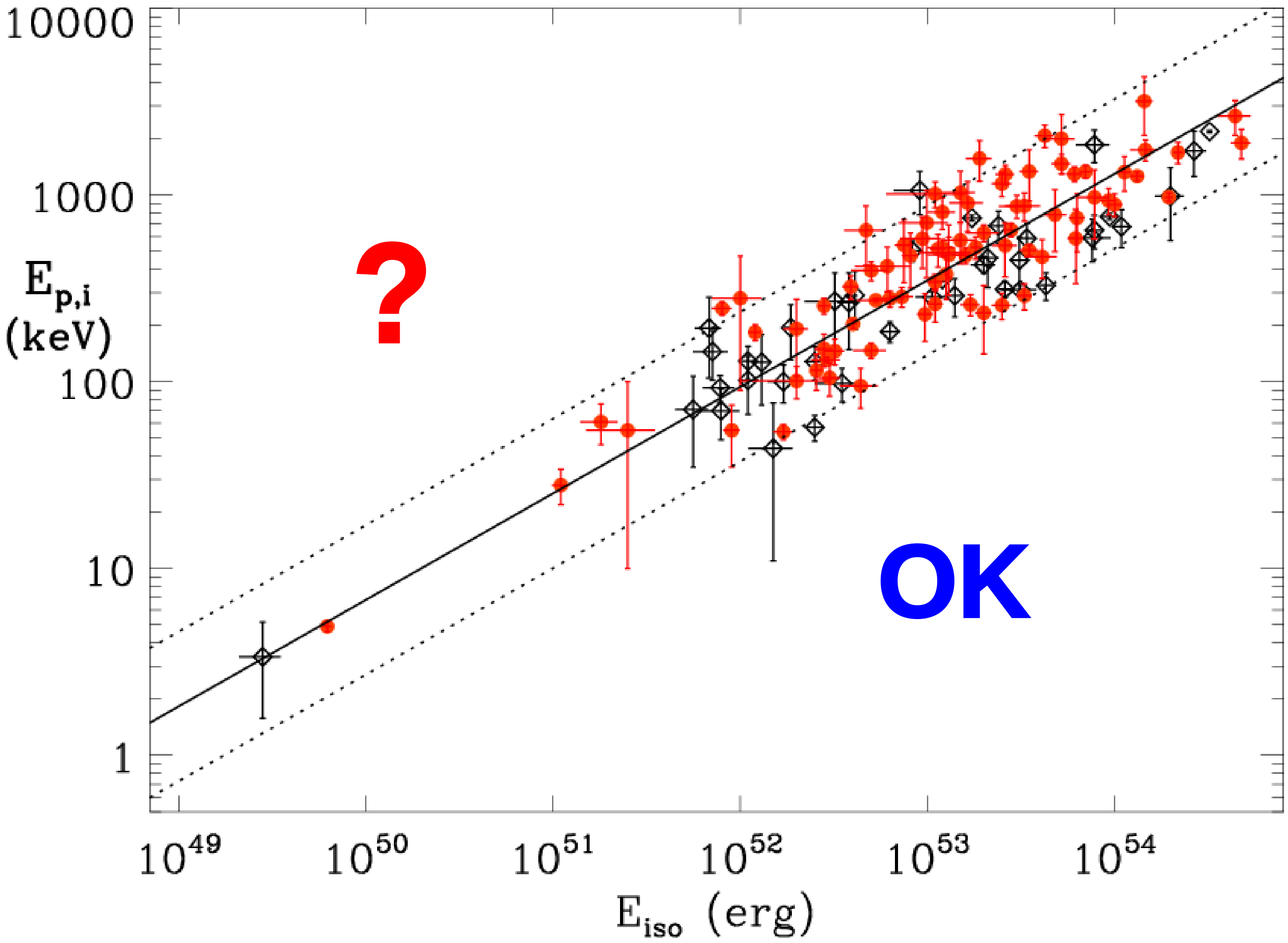


Band 2008

➢ 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)





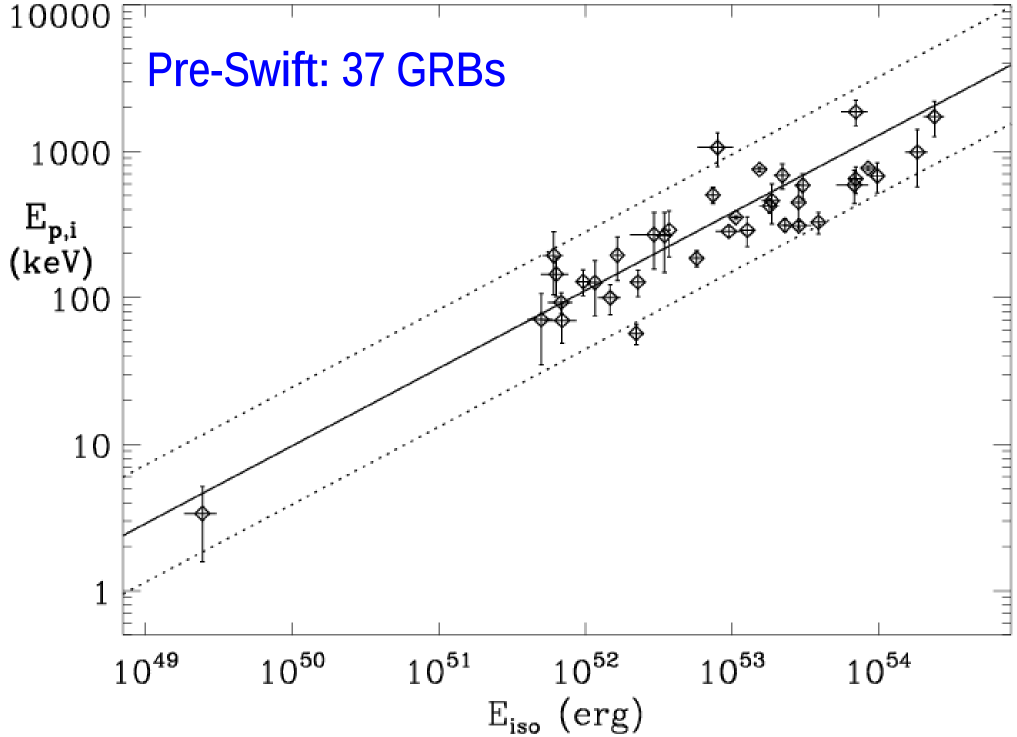


10000
1000
100
10
1
$E_{p,i}$ (keV)
?
OK
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
E_{iso} (erg)

GRBs WITH measured redshift

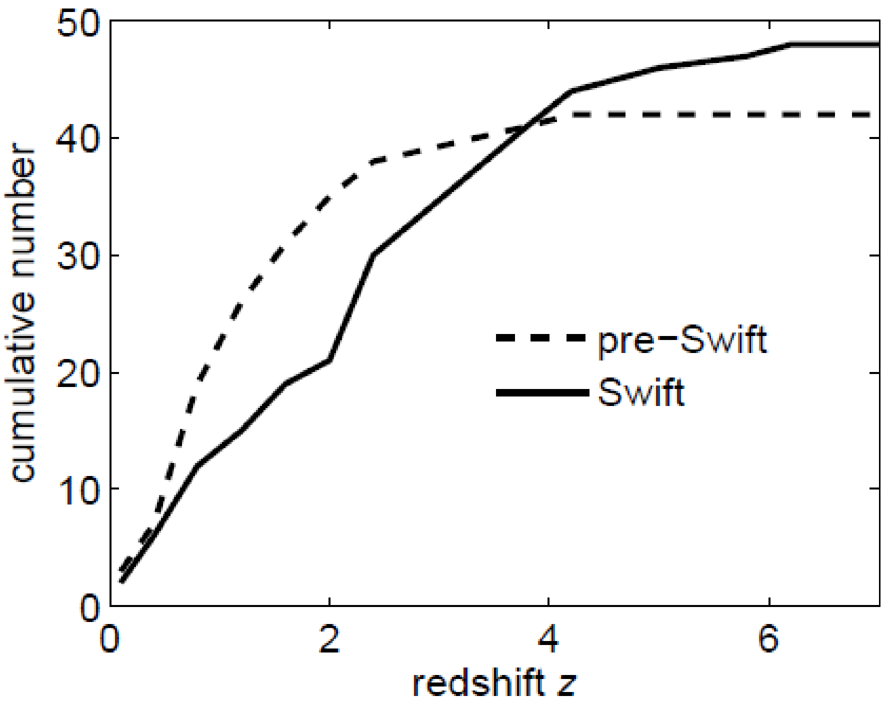
❑ Swift era: substantial increase of the number of GRBs with known redshift: ~45 in the pre-Swift era (1997-2003), ~230 in the Swift era (2004-2012)

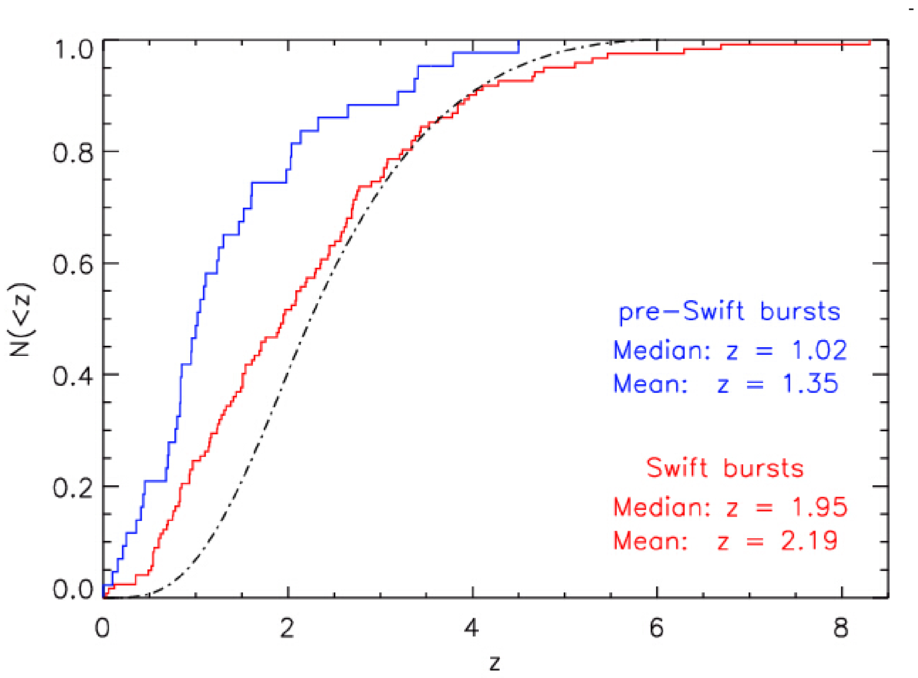
➢ thanks also to combination with other GRB experiments with broad energy band (e.g., Konus/WIND, Fermi/GBM), substantial increase of GRBs in the Ep,i – Eiso plane



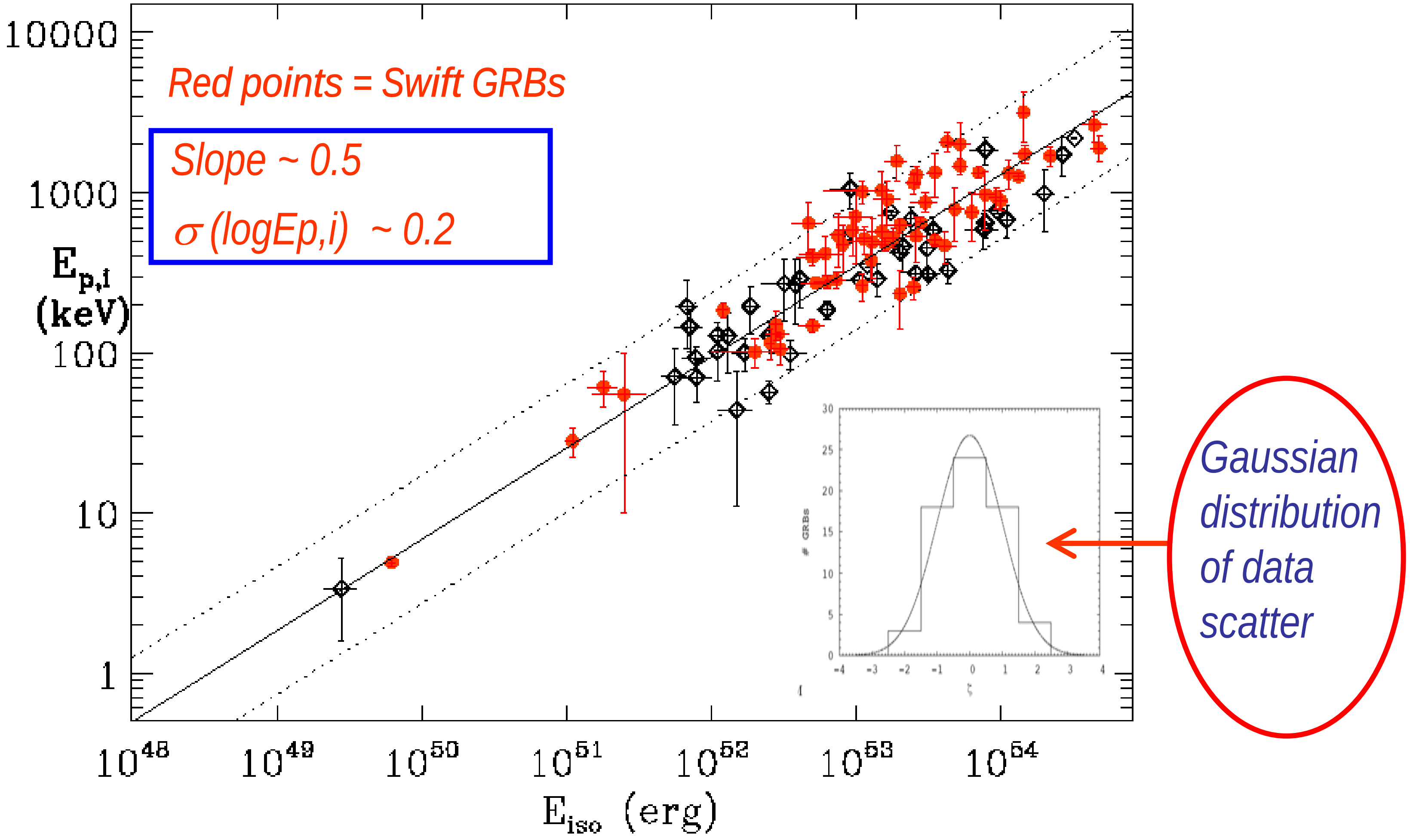
➢ selection effects are likely to play a relevant role in the process leading to the redshift estimate (e.g., Coward 2008, Jakobbson et al. 2010)

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





➢ 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



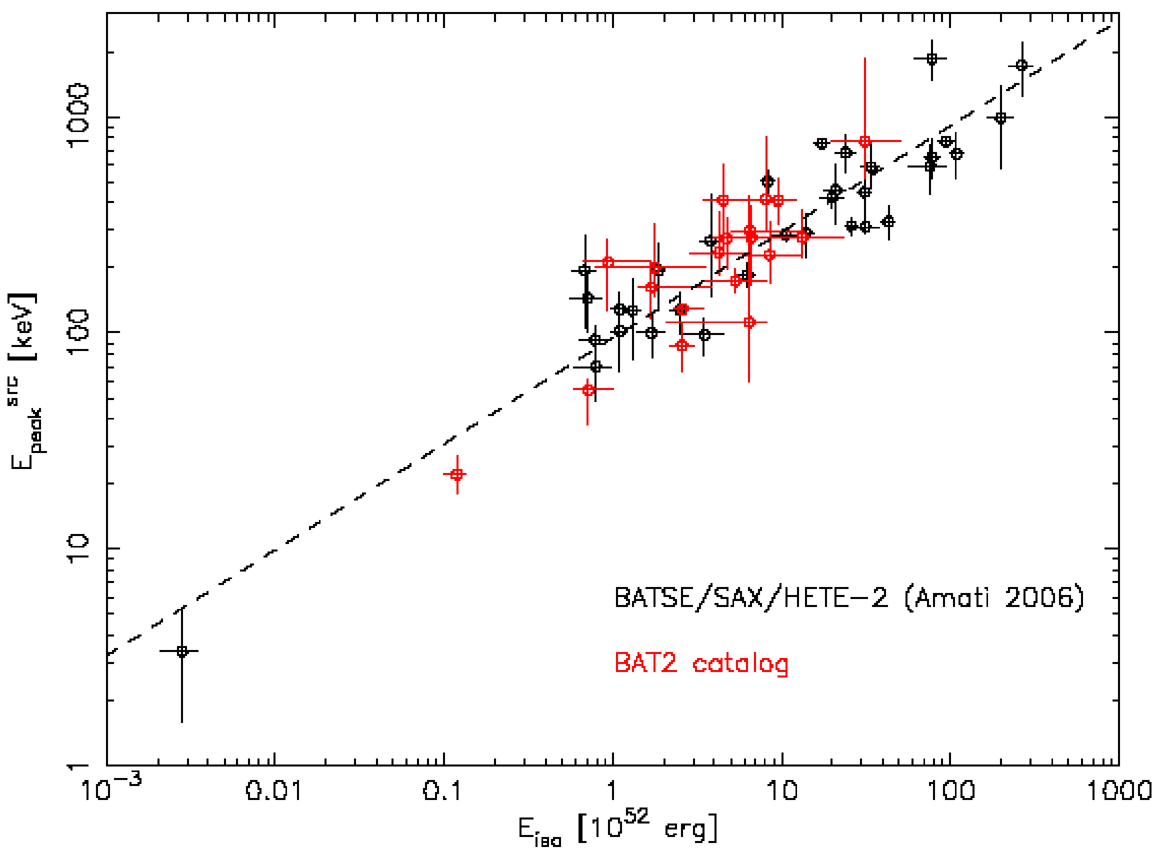
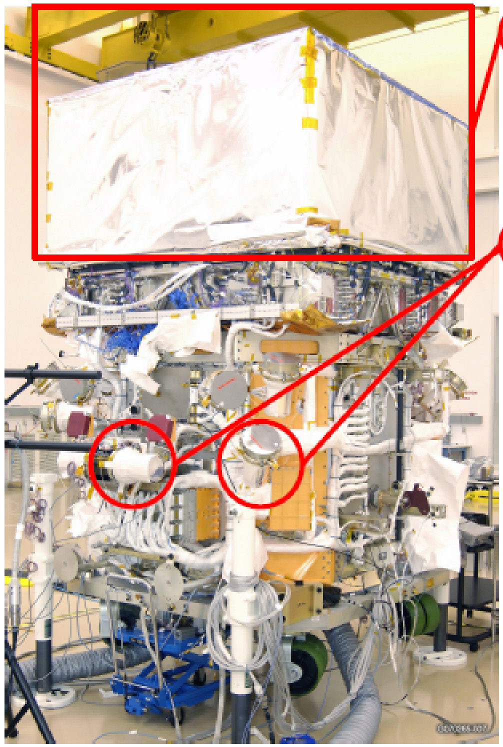


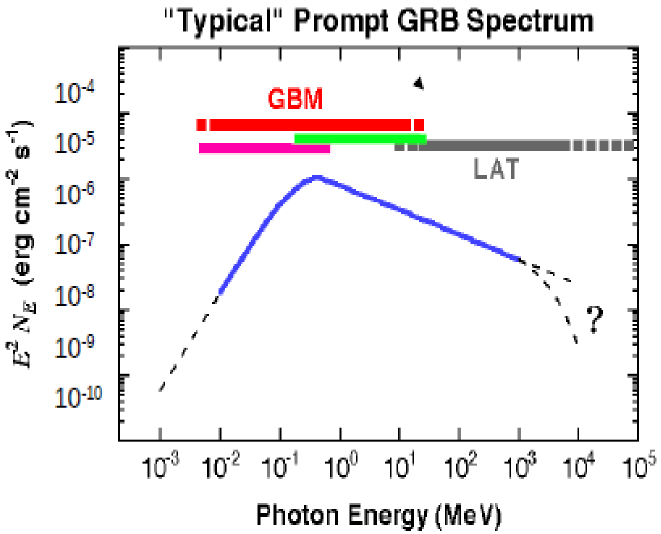
Fig. 33.— The correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ for the *Swift* GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ reported by Amati (2006): $E_{\rm peak}^{\rm src} = 95 \times (E_{\rm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

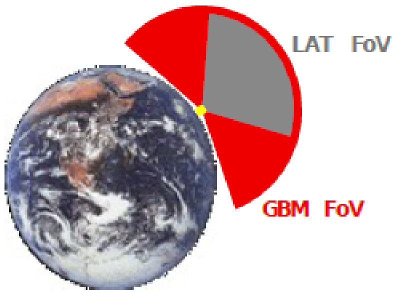
Sakamoto et al. 2011

- 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



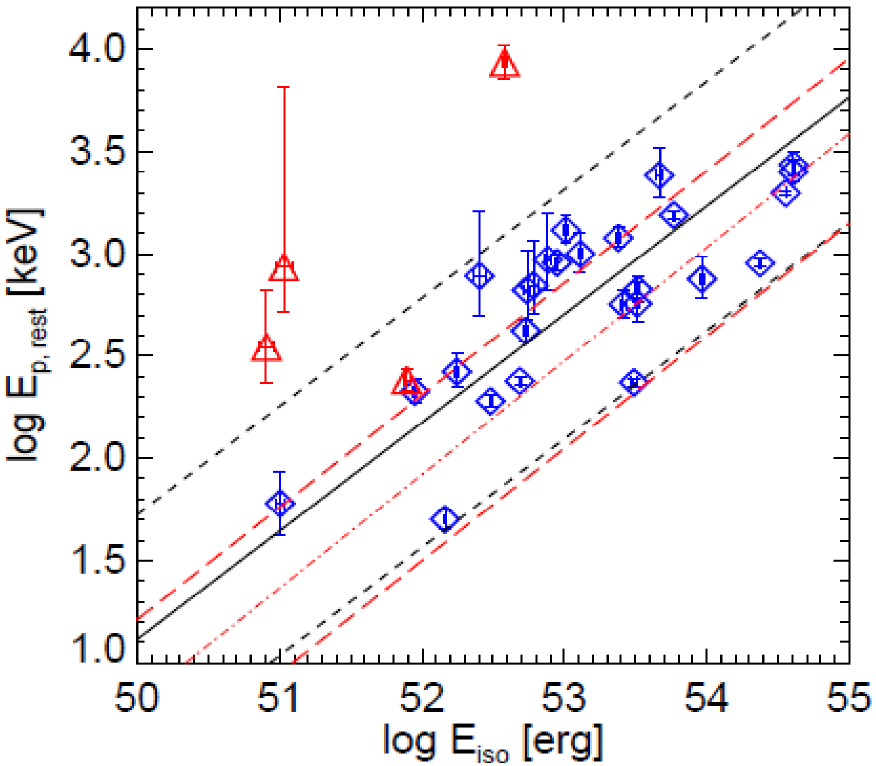
- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.

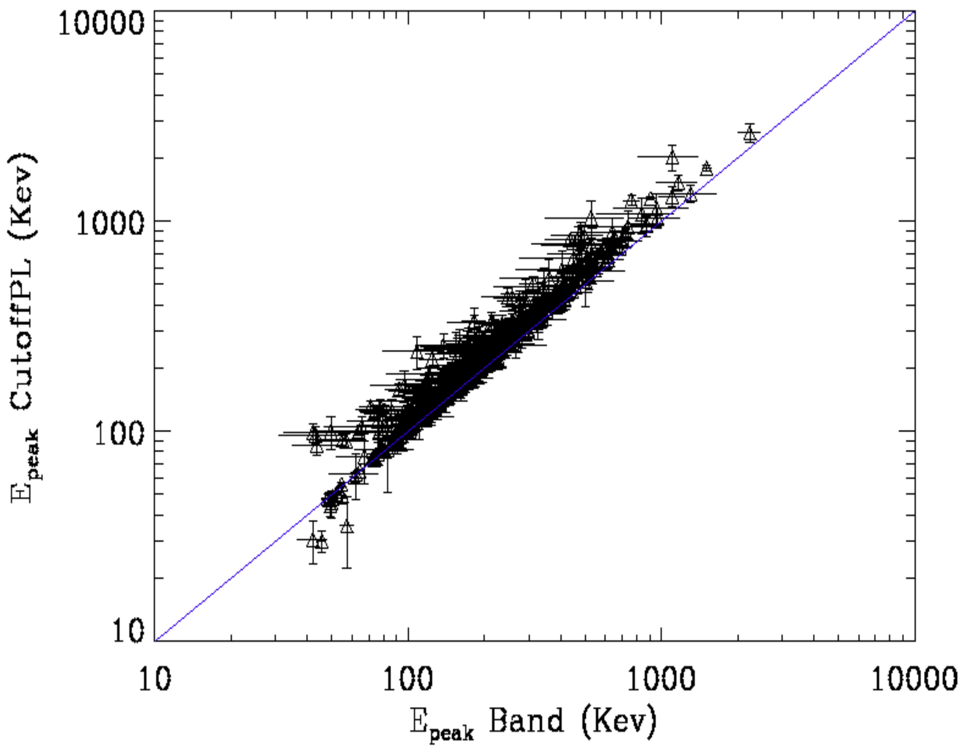




- *Gruber et al (2011, official Fermi team): all Fermi/*GBM long GRBs with known z are consistent with Ep,i – Eiso correlation, short GRBs are not

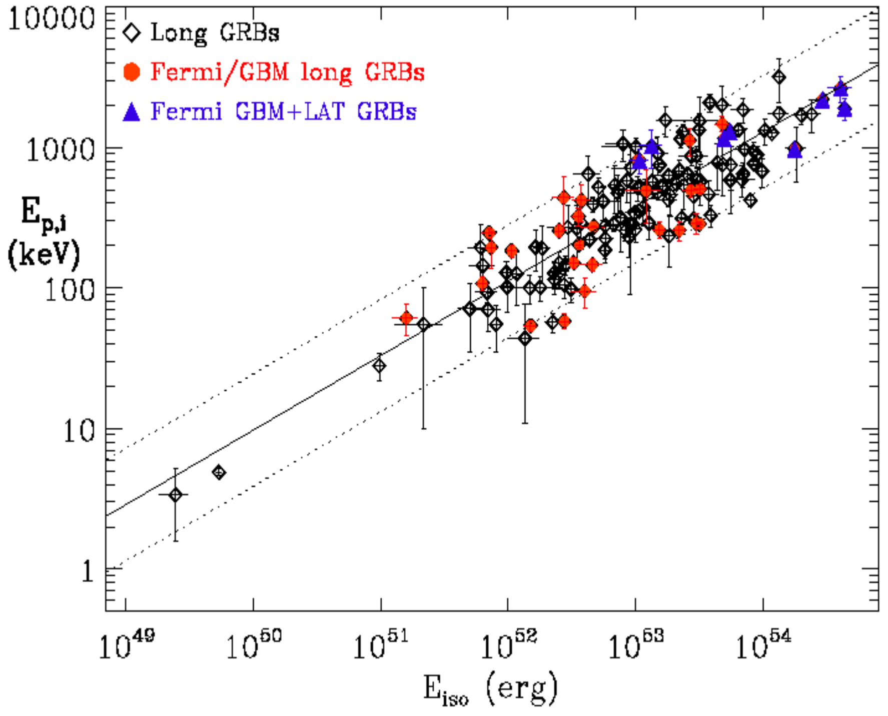
- slight overestimate of normalization and dispersion possibly due to the use, for some GRBs, of the CPL model instead of the Band model (-> overestimate of Ep, underestimate of Eiso)



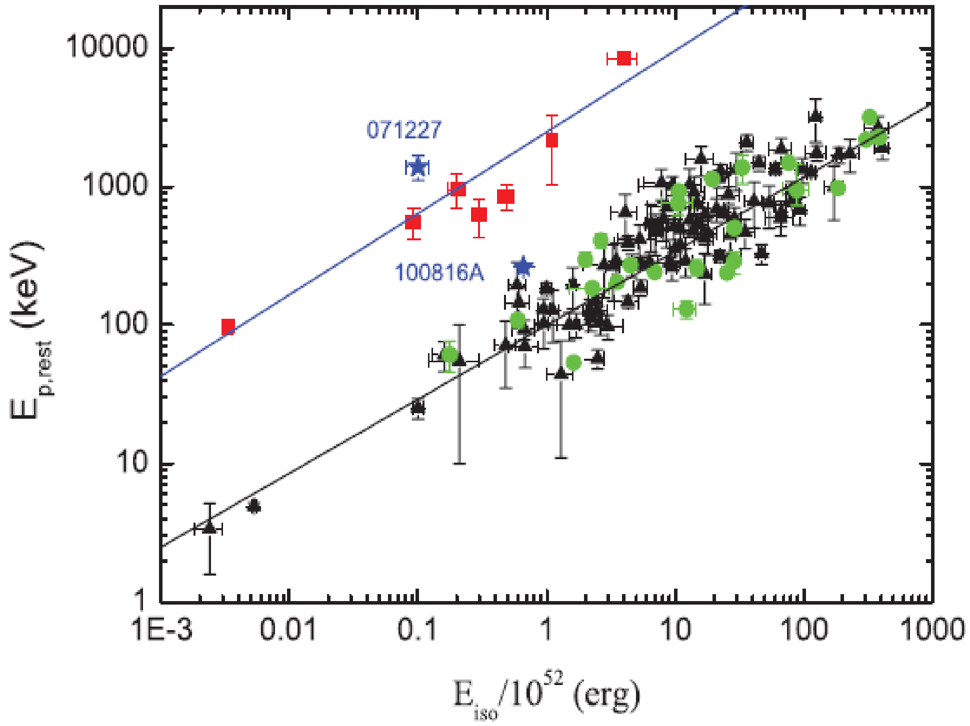


Gruber et al. 2011

❑ 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)

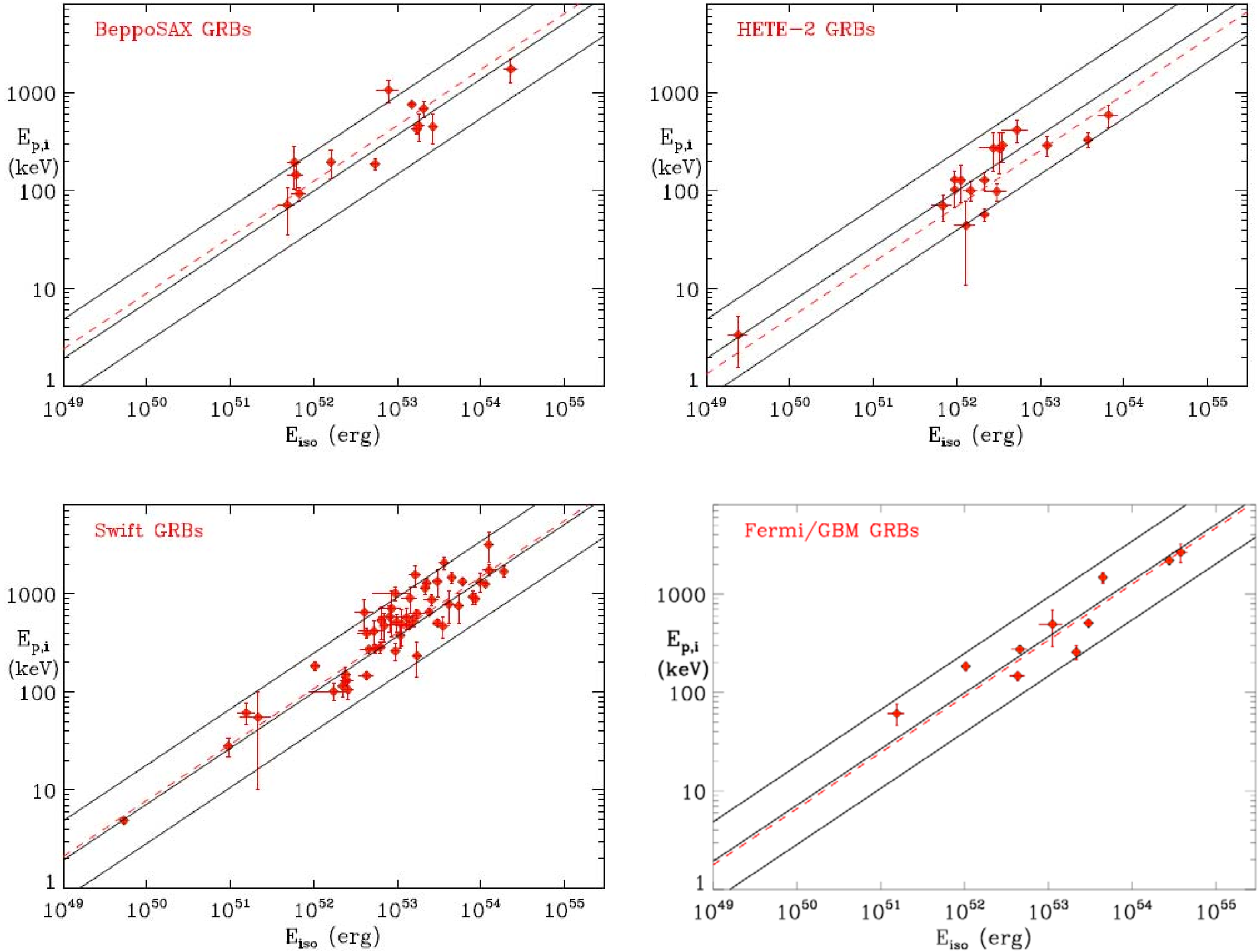


Amati 2012

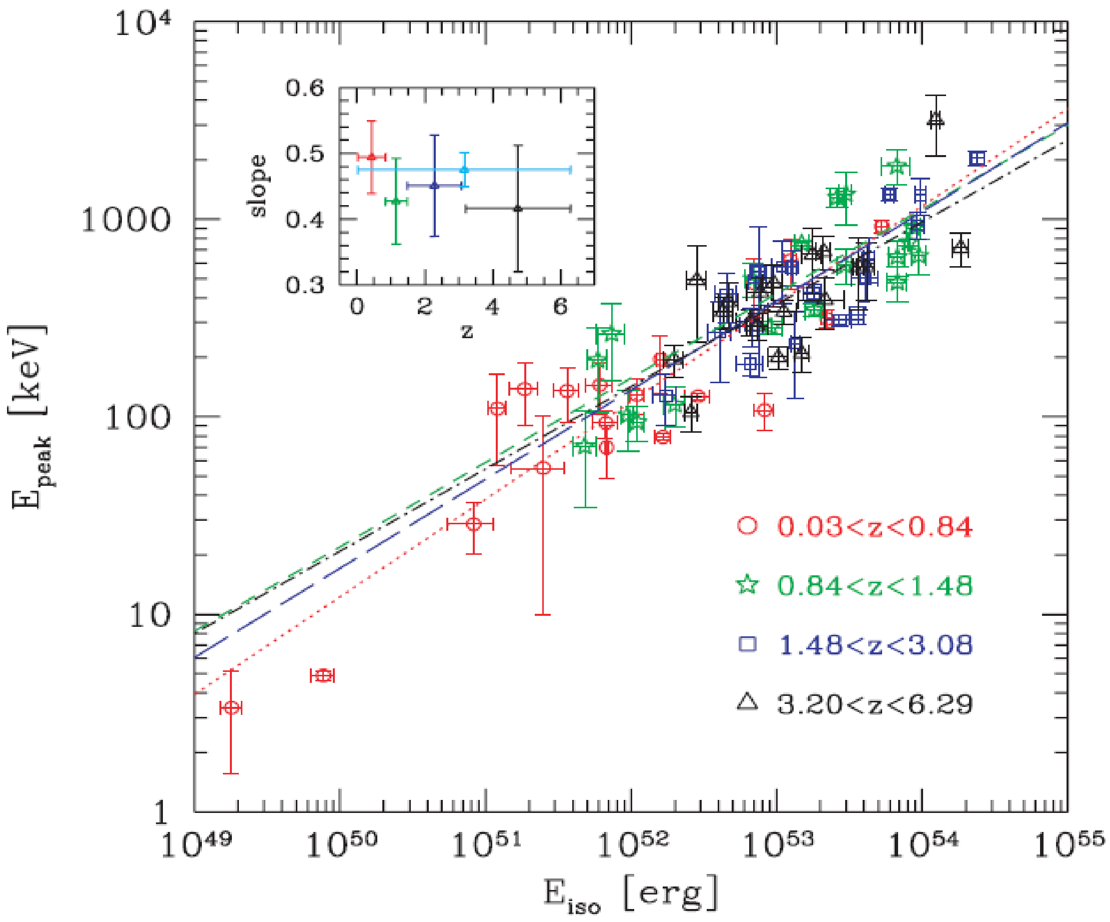


Zhang et al. 2012

❑ 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



❑ 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

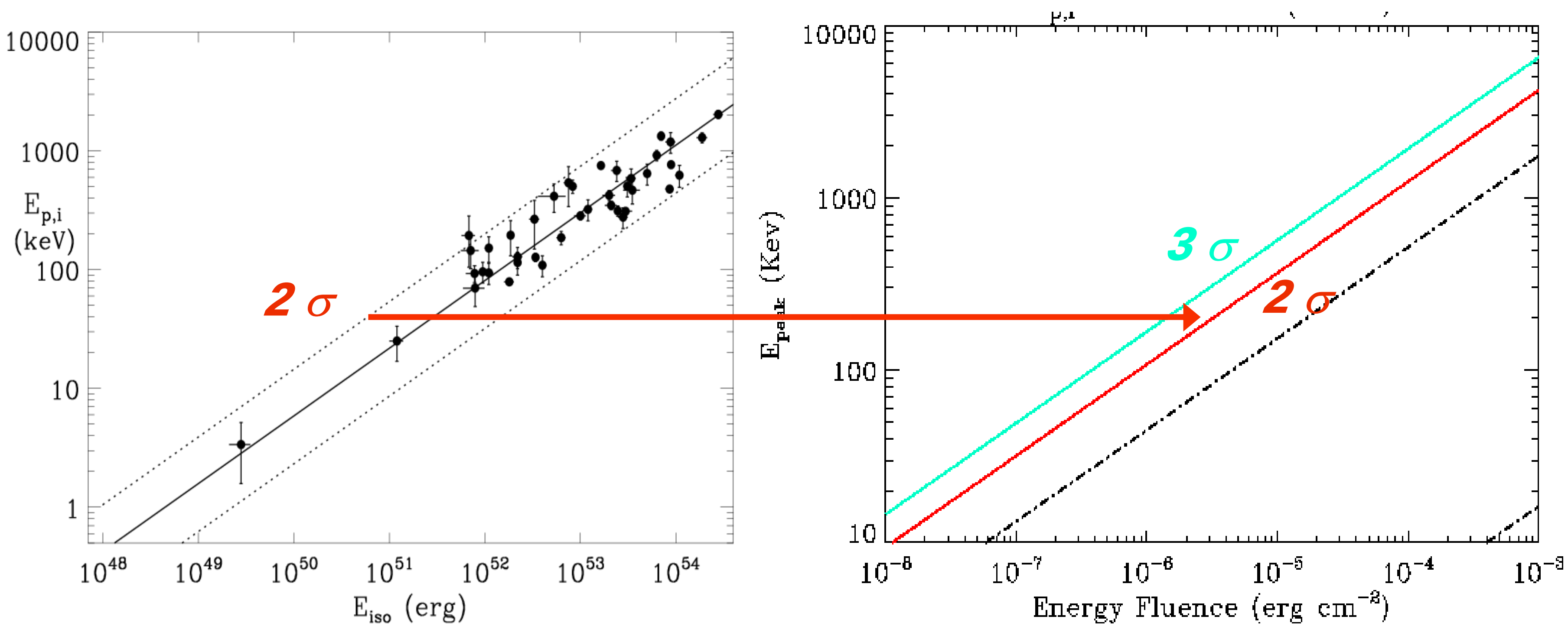
- moreover: the existence of an Ep,i – Eiso correlation was supposed by Lloyd, Petrosian & Mallozzi in 2001 based on BATSE data

- 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)

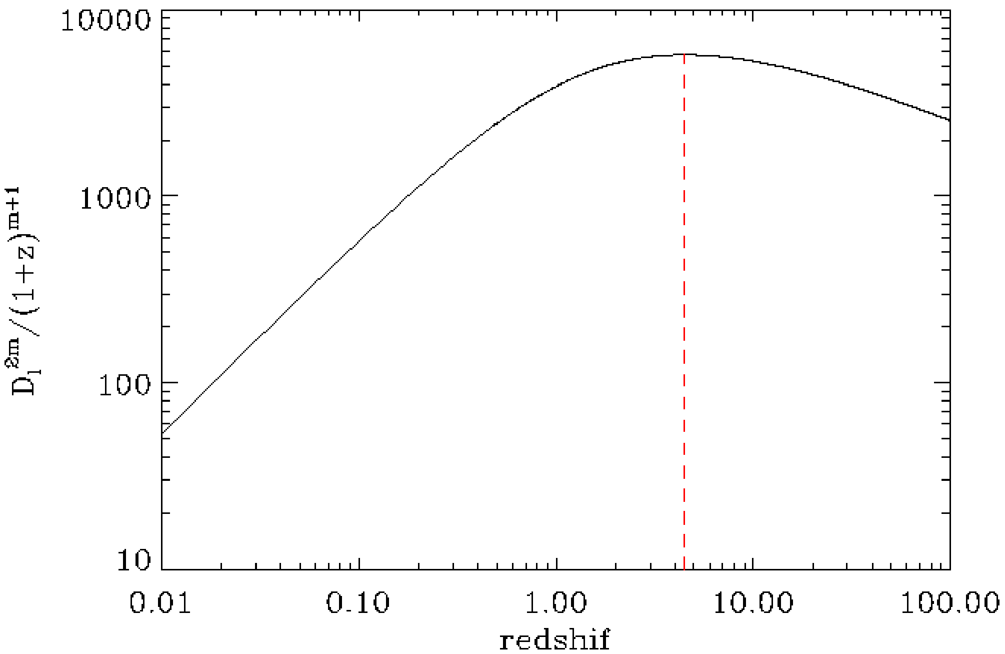
GRBs WITHOUT redshift (thousands)

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

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

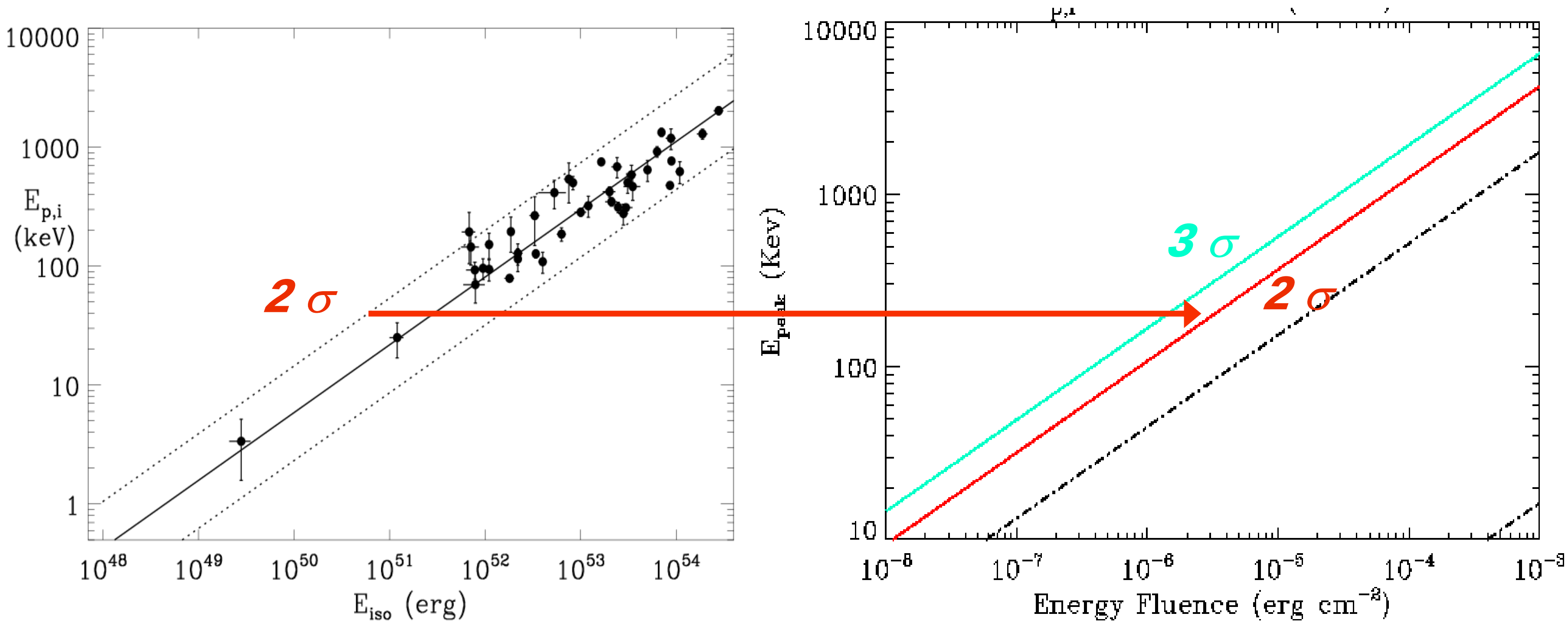
- the fit of the updated Ep,i – Eiso GRB sample with the maximum –likelihood method accounting for extrinsic variance provides a=0.53, k= 102, σ = 0.19

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



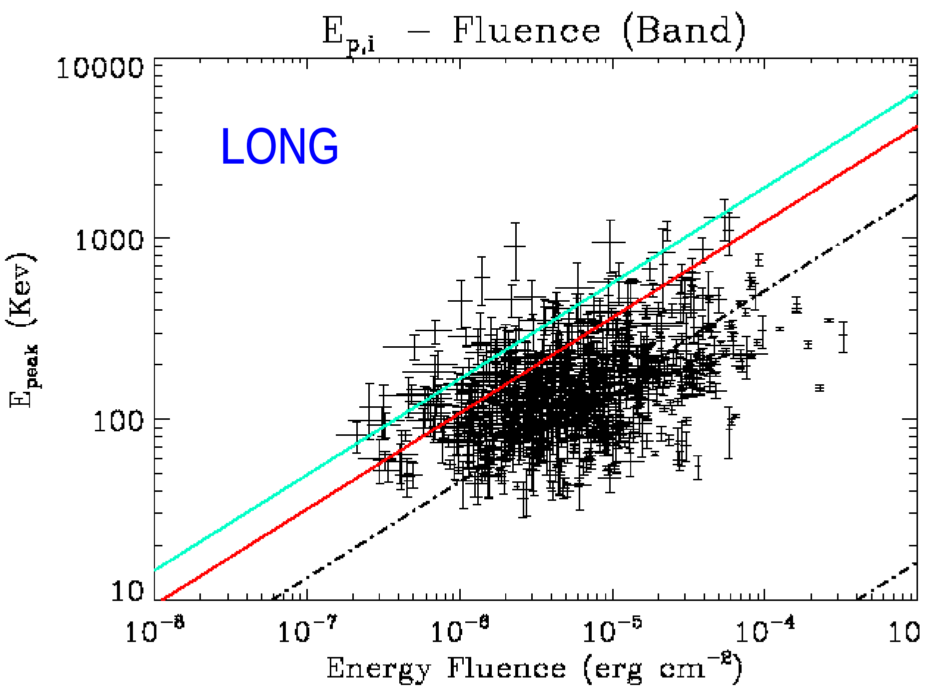
Intrinsic (cosm. Rest-frame) plane

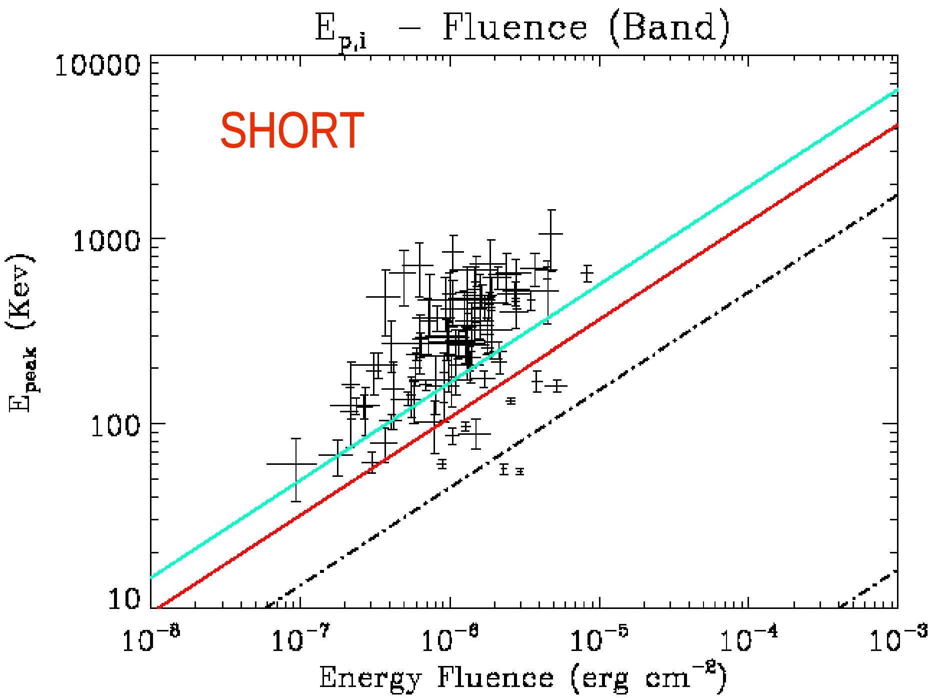
Observer's plane



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

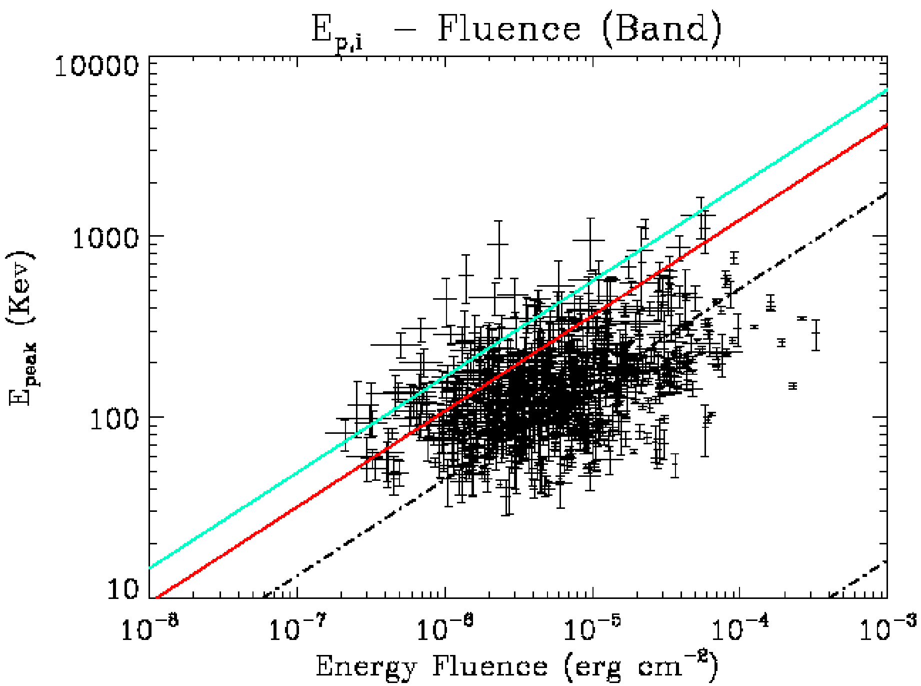
❑ considered long (777) and short (89) GRBs with fit with the Band-law and uncertainties on Ep and fluence < 40%



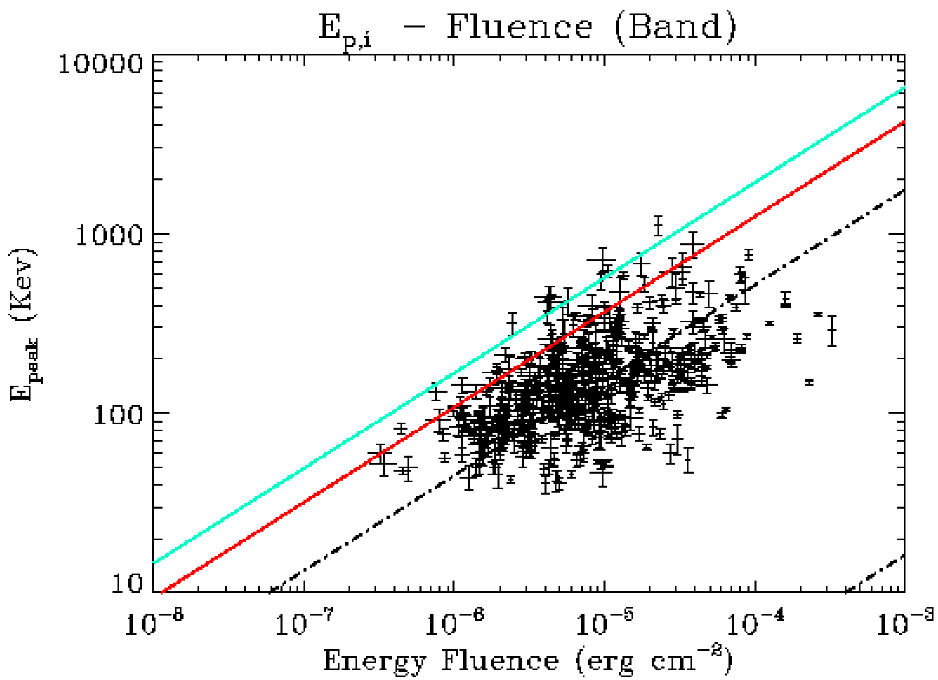


➢ most long GRBs are potentially consistent with the Ep.i – Eiso correlation, most short GRBs are not

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



LONG, 40% unc.



LONG, 20% unc.

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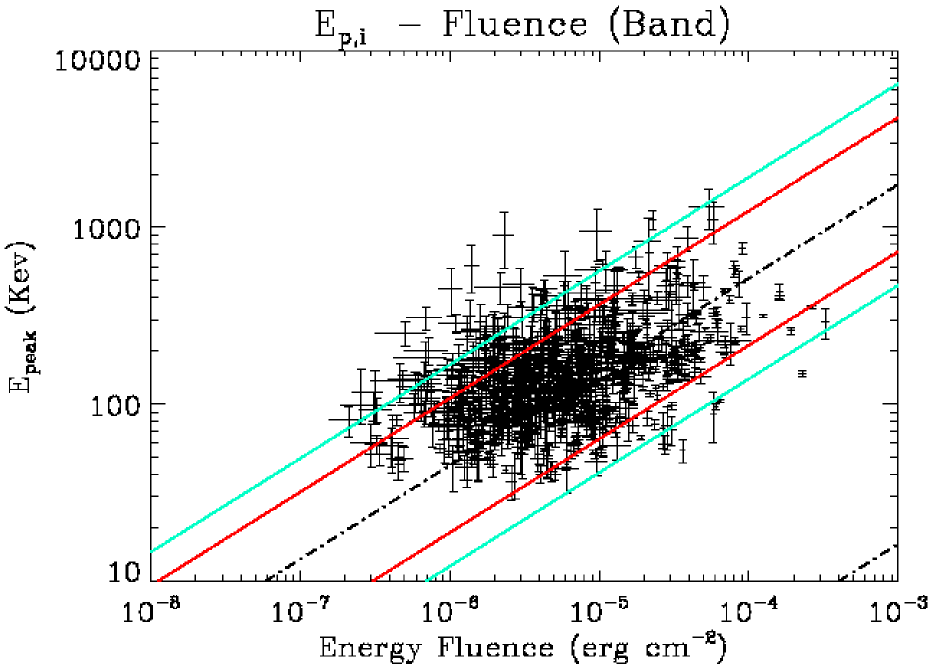
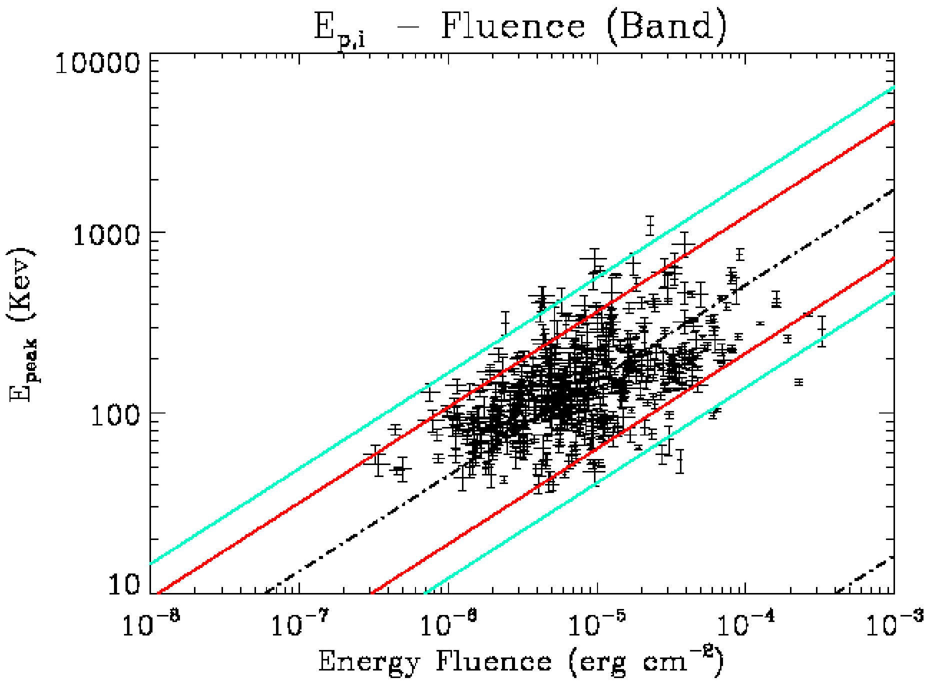


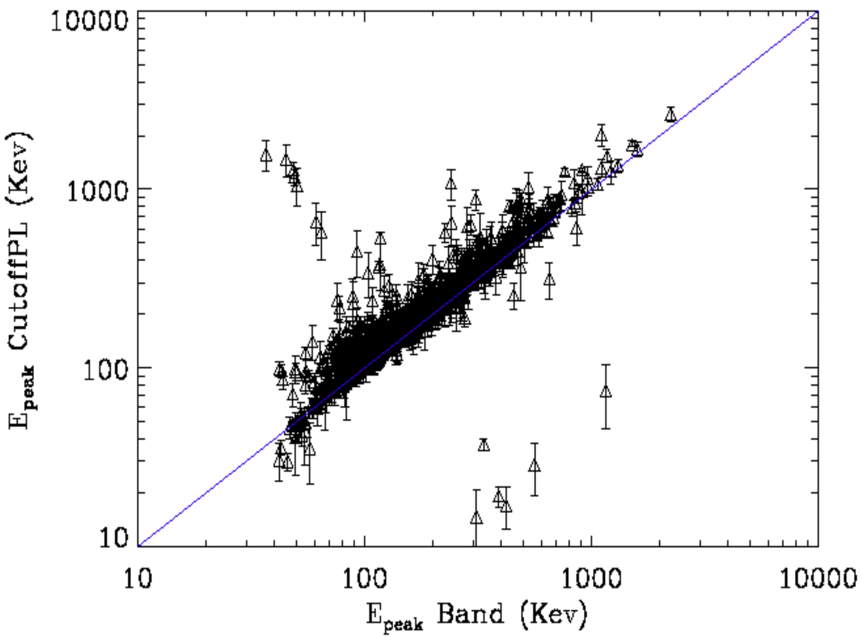
LONG, 40% unc.

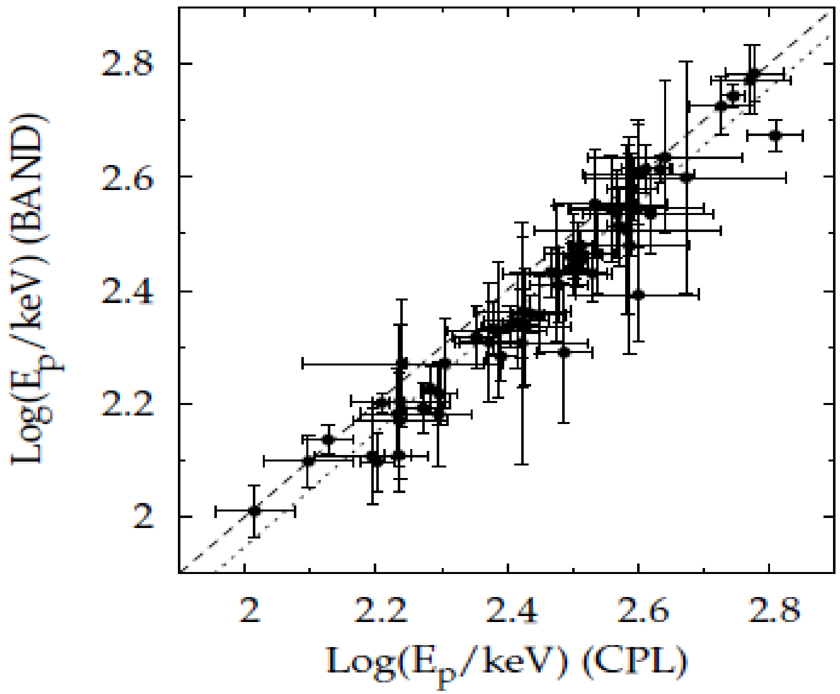


LONG, 20% unc.

- 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

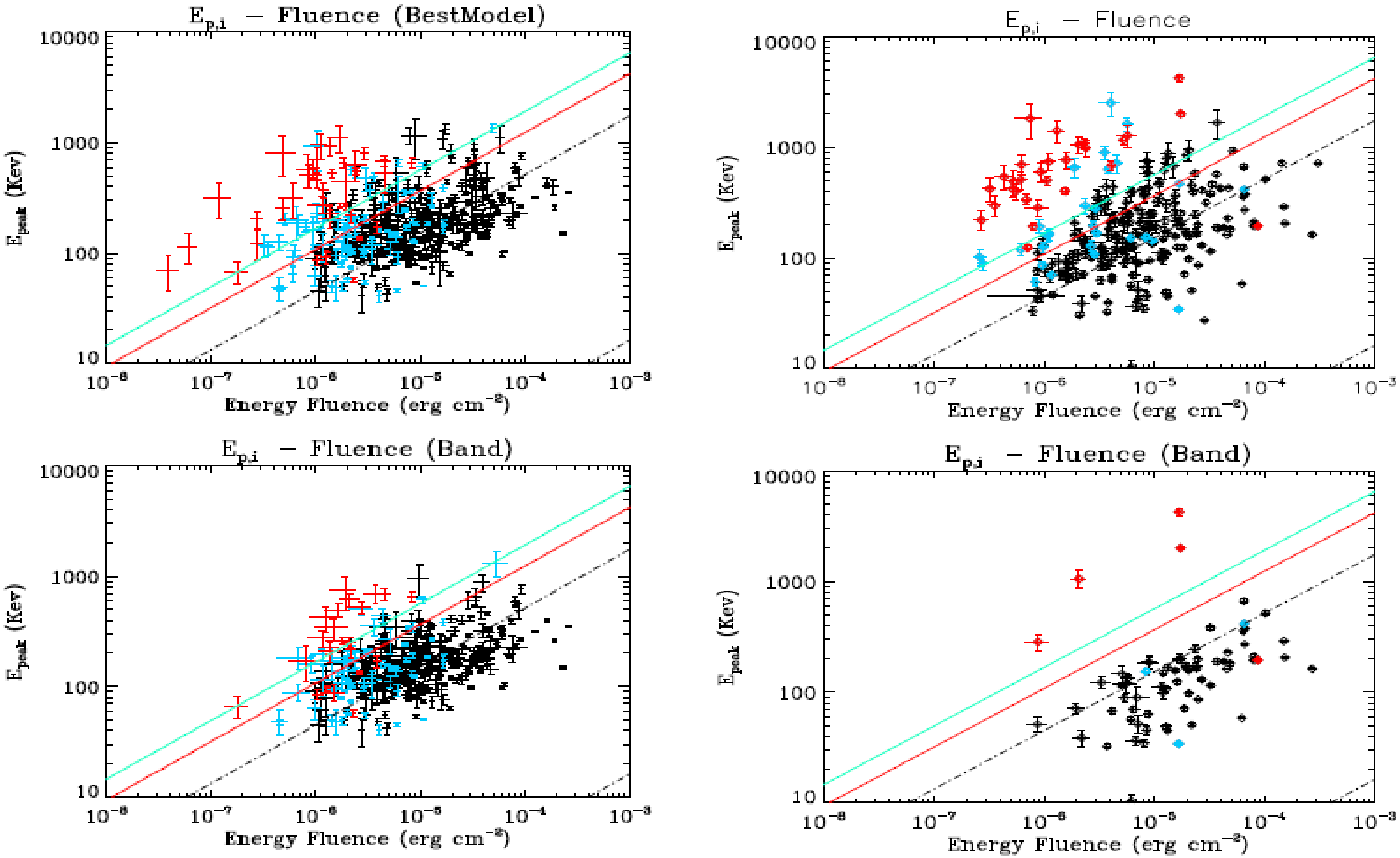




BATSE, sample of Goldstein et al. 2010

BeppoSAX/GRBM (Guidorzi et al. 2010)

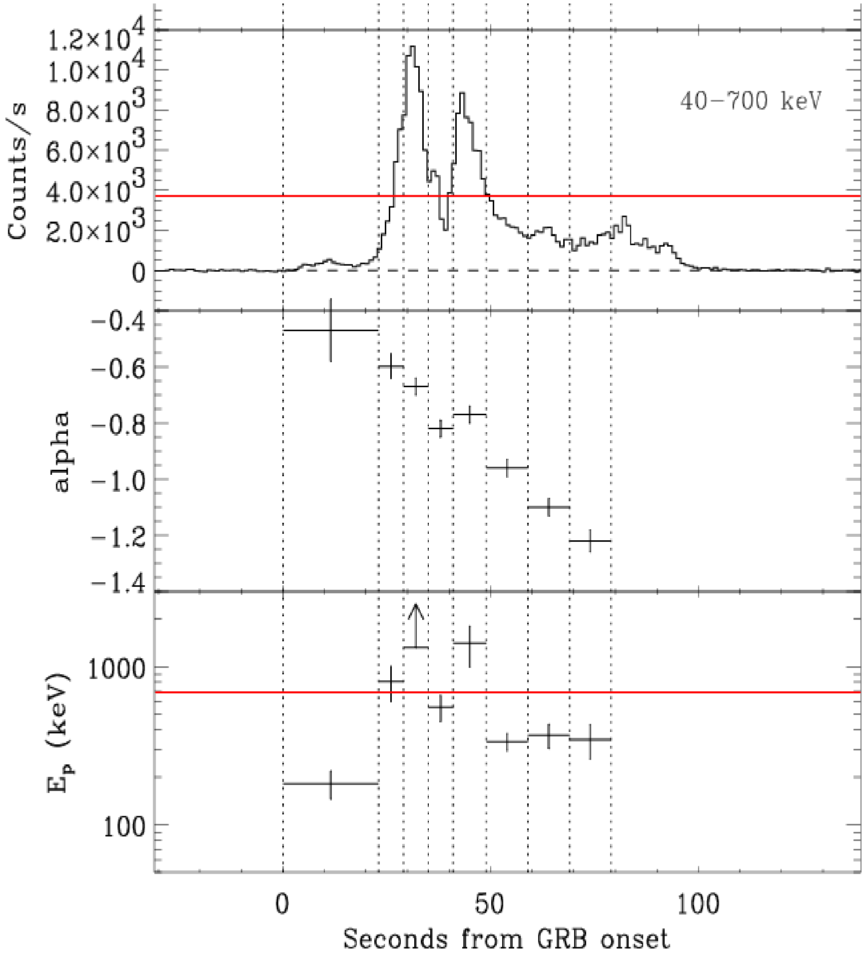
❑ ALL long BATSE and Fermi long GRBs with Ep and fluence derived form fit with Band function are potentially consistent with the correlation

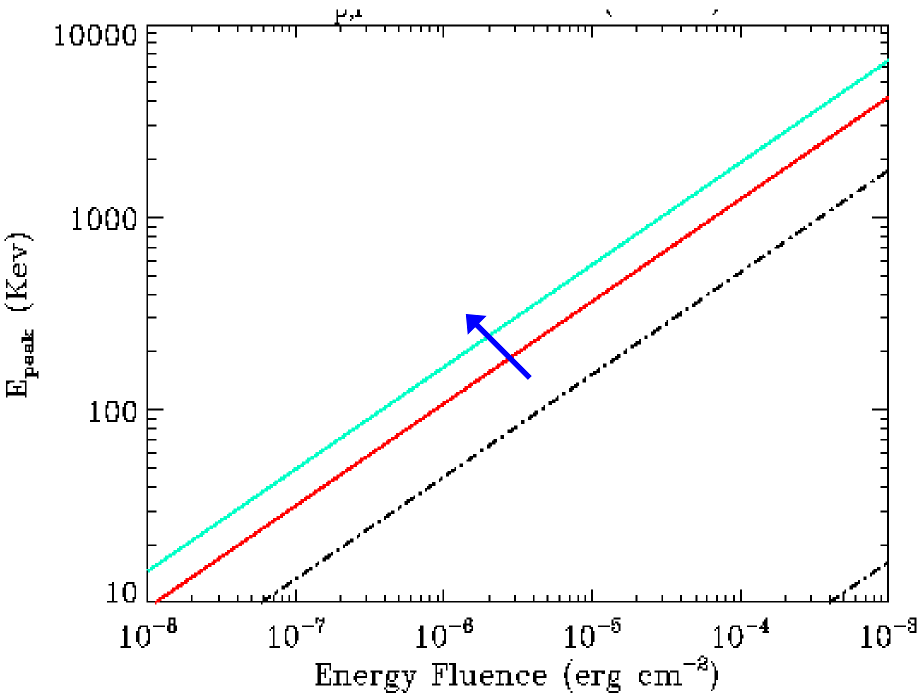


BATSE (data from Goldstein+10)

Fermi (data from Nava+11)

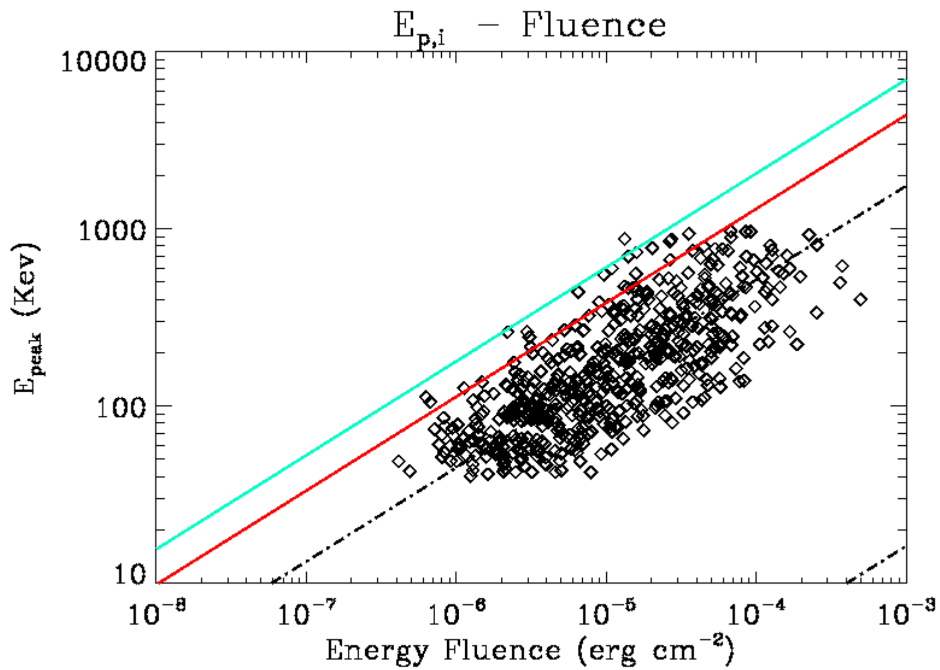
b) measure only the harder portion of the event: overestimate of Ep and underestimate of the fluence

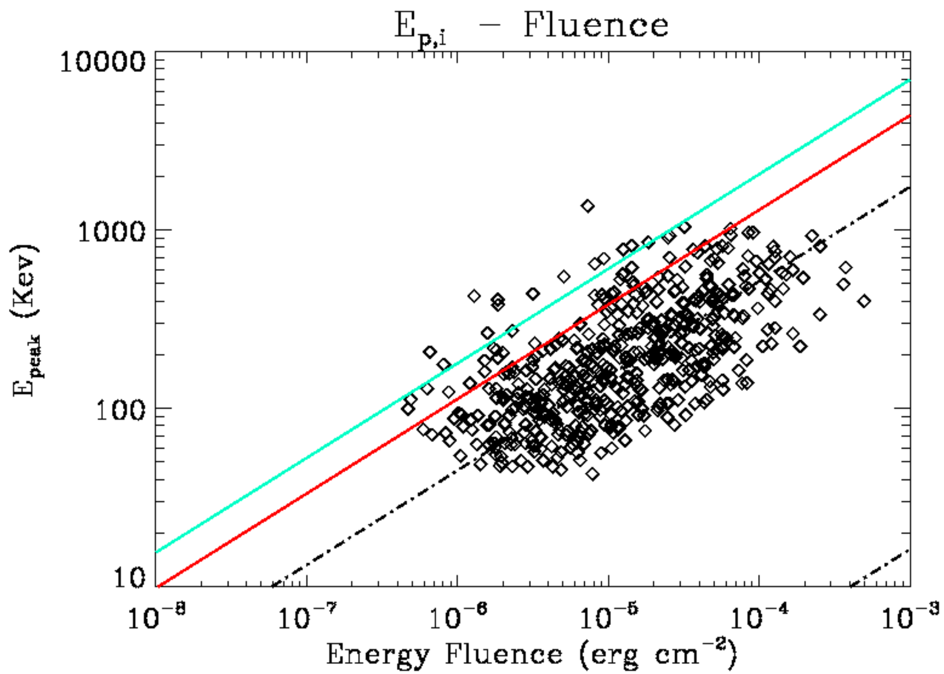




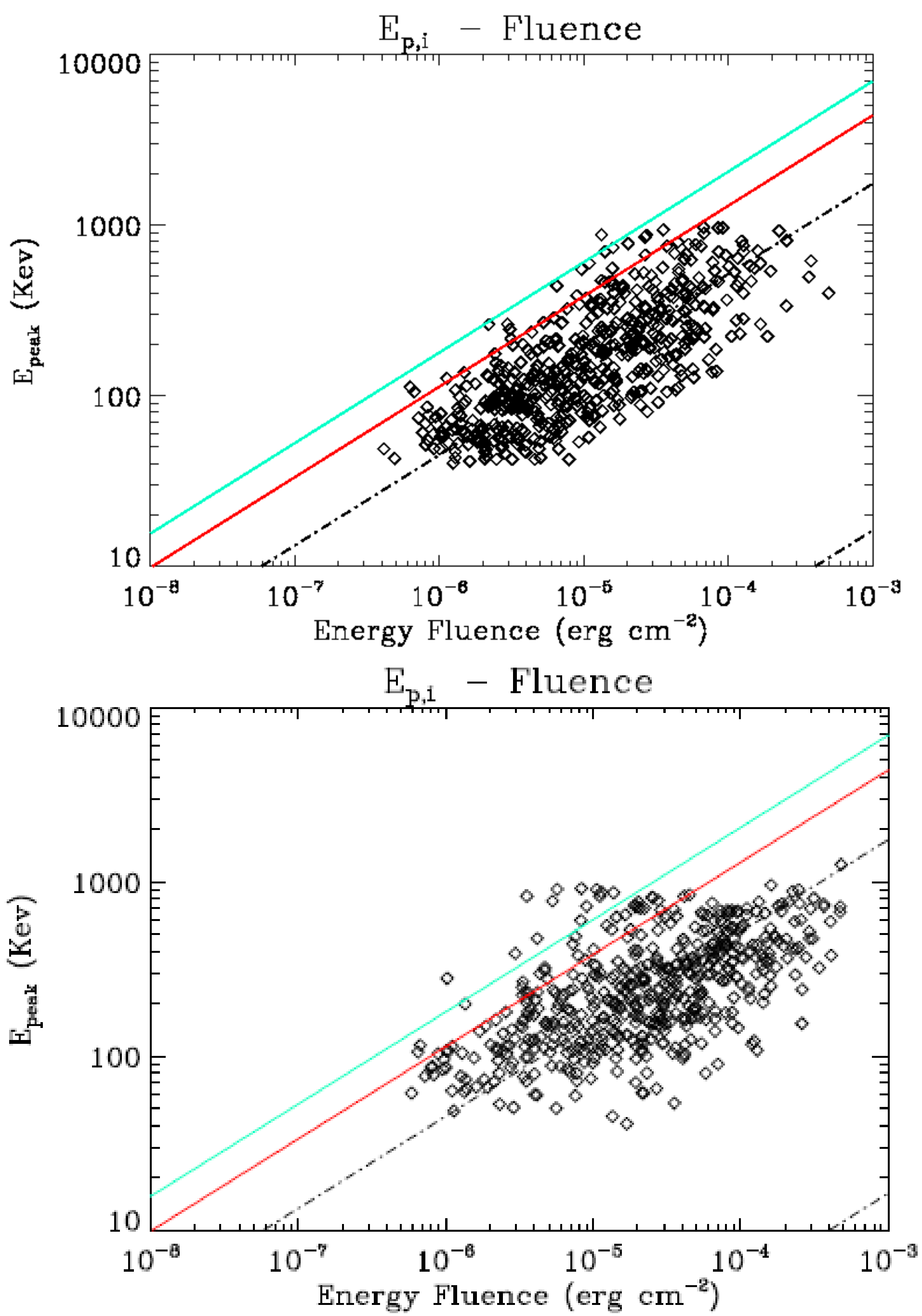
- Amati, Dichiara et al. (2011, in prep.): MC simulations assuming the existence and the measured parameters of the Ep,i – Eiso correlation and accounting for the observed distributions (Eiso, z, Eiso vs. z) and BATSE instrumental sensitivity as a function of Ep (Band 2003-2009)

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



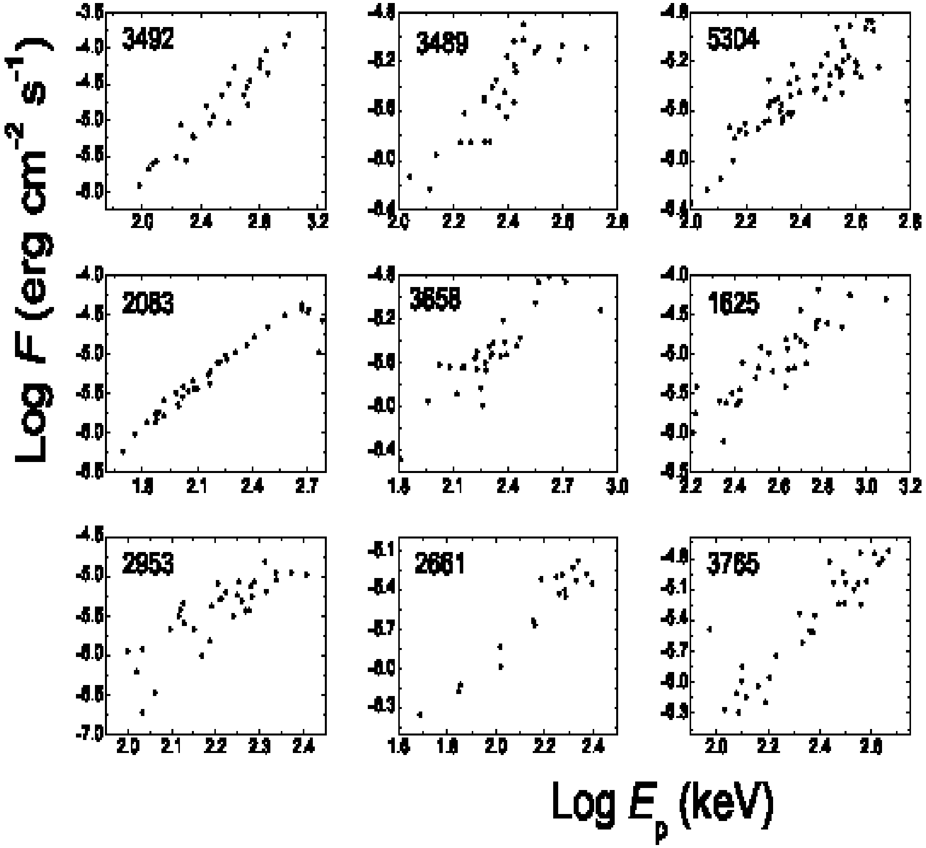


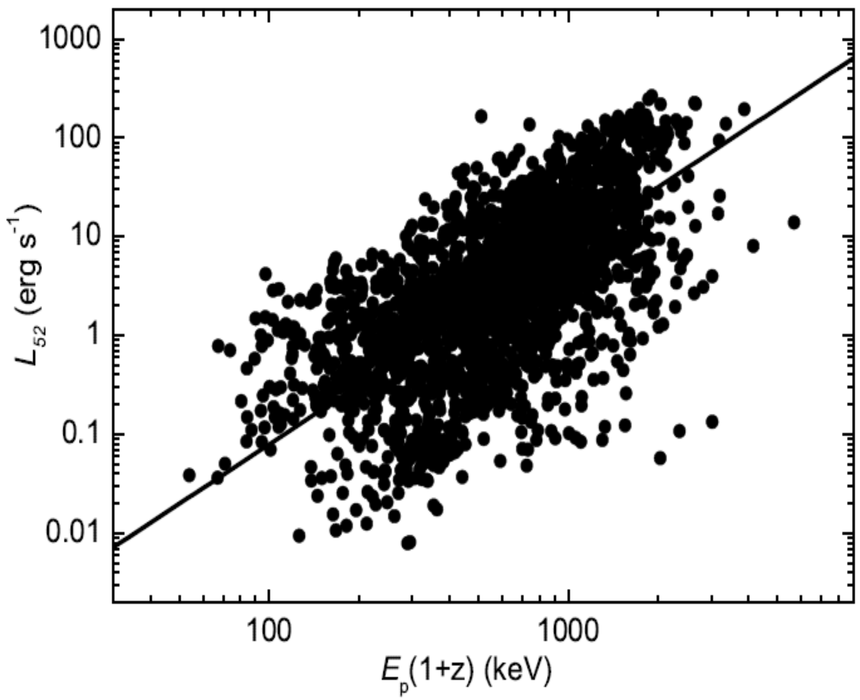
- Amati, Dichiara et al. (2011, in prep.): MC simulations assuming the existence and the measured parameters of the Ep,i – Eiso correlation and accounting for the observed distributions (Eiso, z, Eiso vs. z) and BATSE instrumental sensitivity as a function of Ep (Band 2003-2009)
- When accounting for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

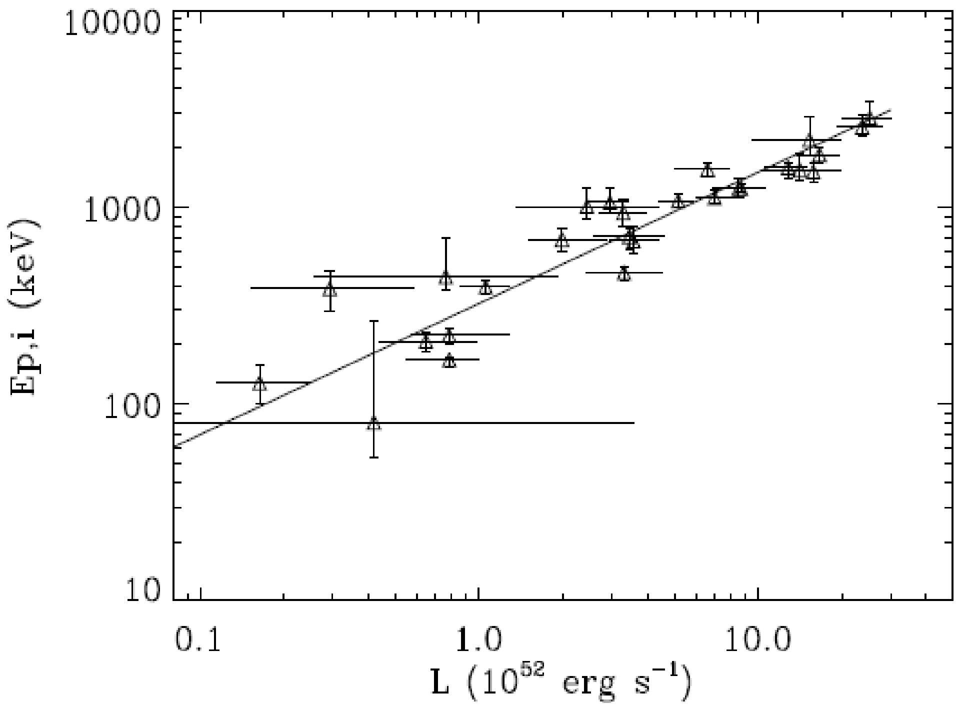
❑ Liang et al.2004: evidence for an Ep – Flux correlation within most BATSE GRBs and, based on pseudo-redshifts, possible existence of a univoque Ep,i(t) – Liso(t) correlation



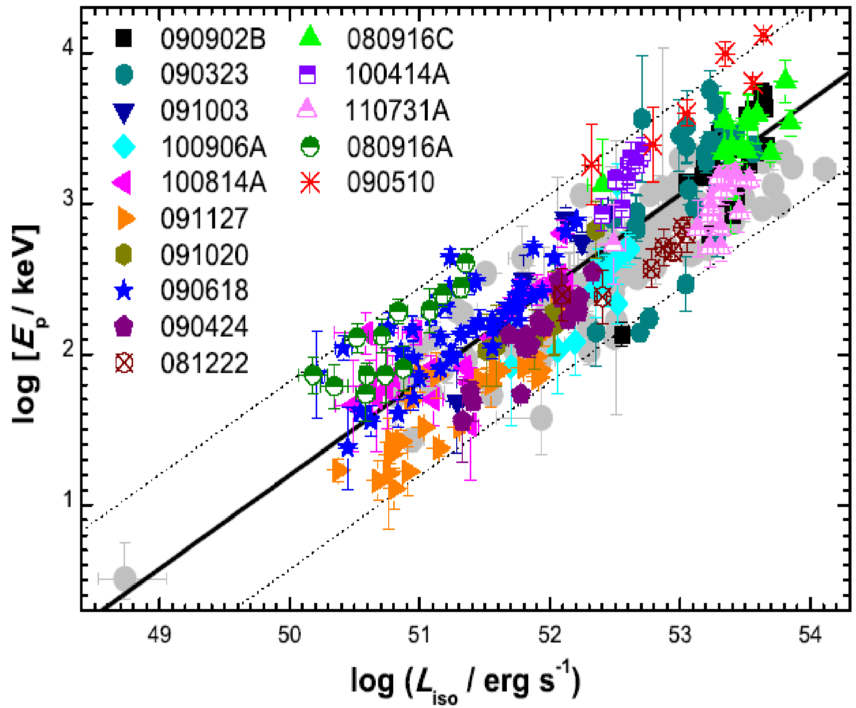


Liang et al., ApJ, 2004

➢ 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



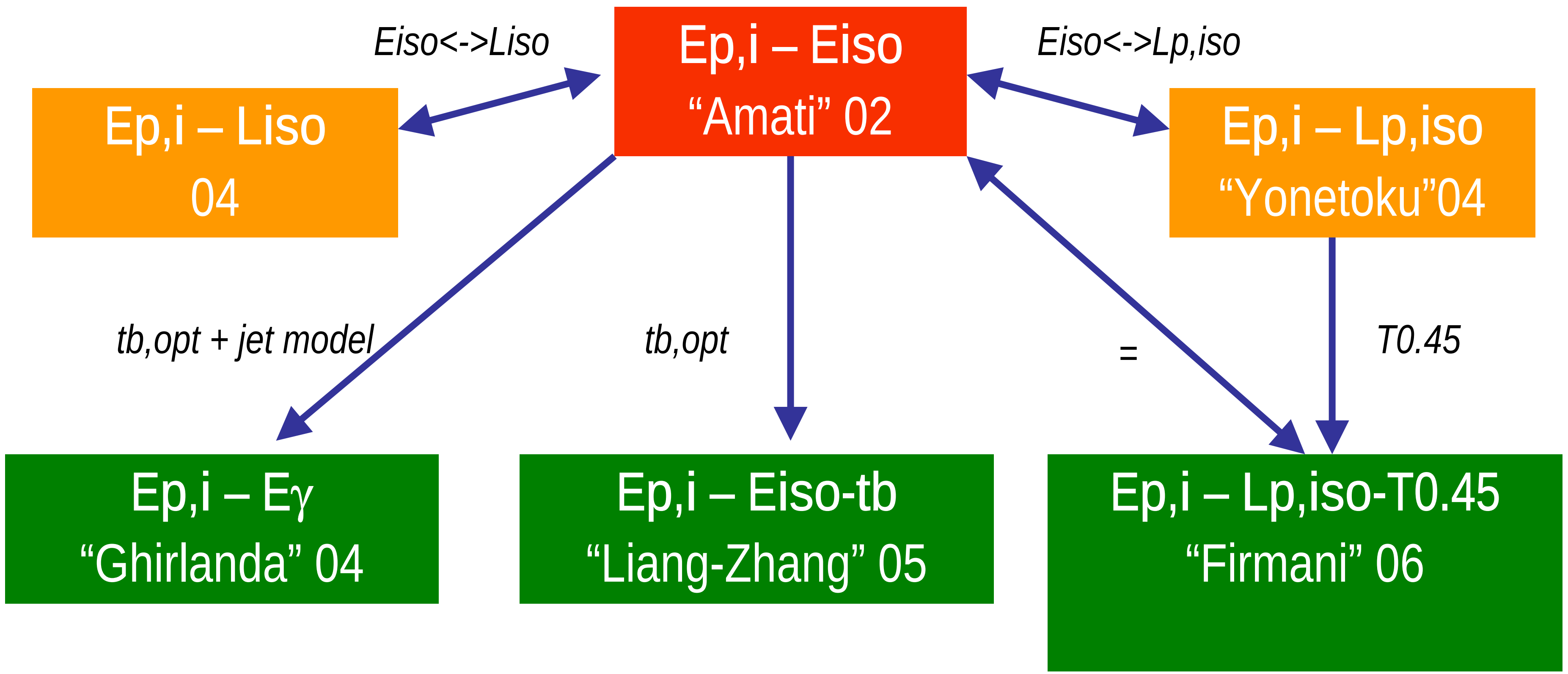
SAX+BATSE (Frontera et al. ApJ, in press)



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

Which "intensity indicator" ?

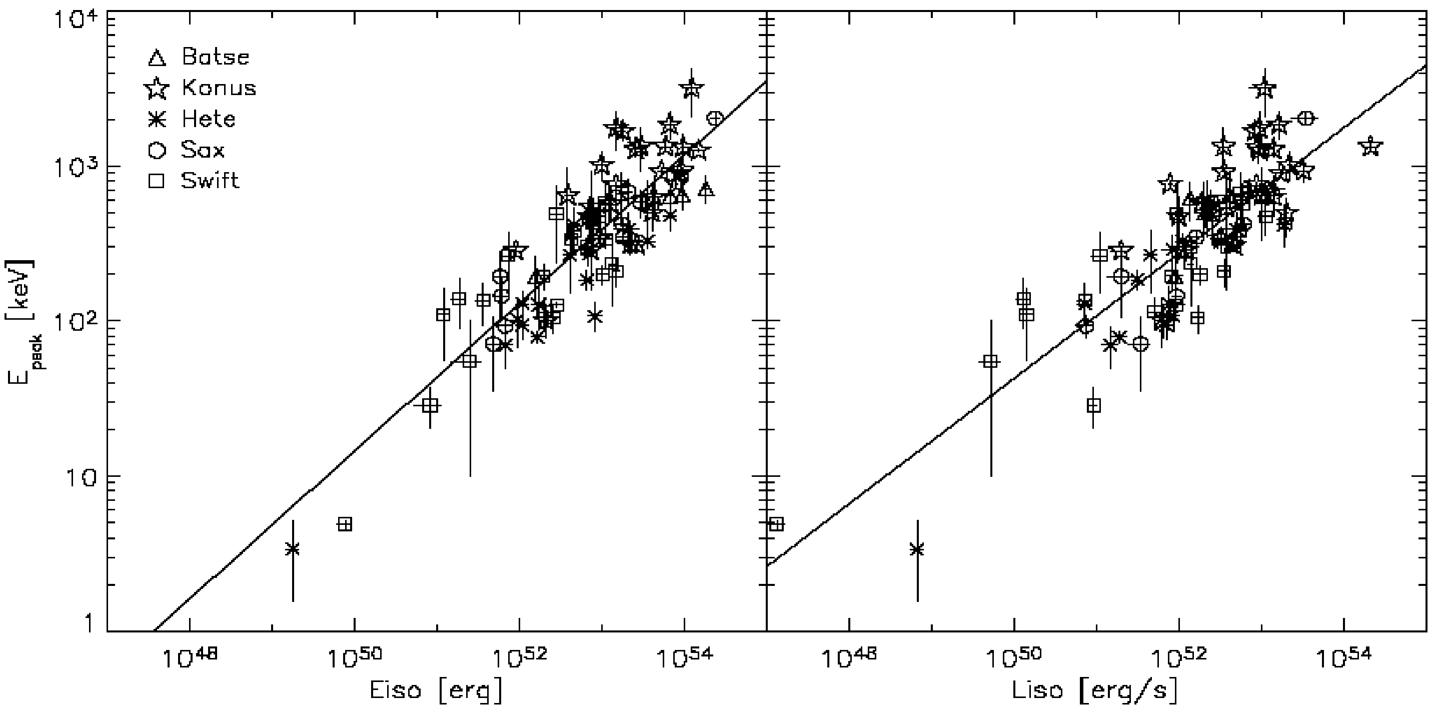
- Ep,i – Eiso vs. other Ep-Intensity correlations



➢ 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)

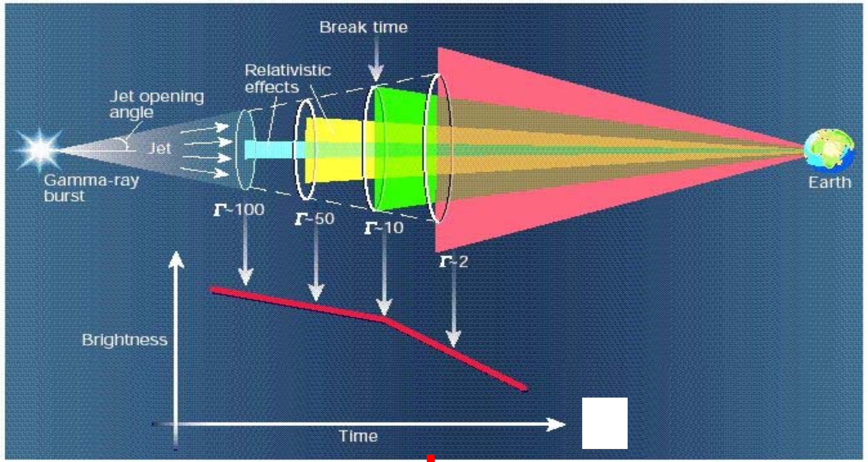
➢ this is expected because Liso and Lpeak,iso are strongly correlated with Eiso

➢ 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 ?)



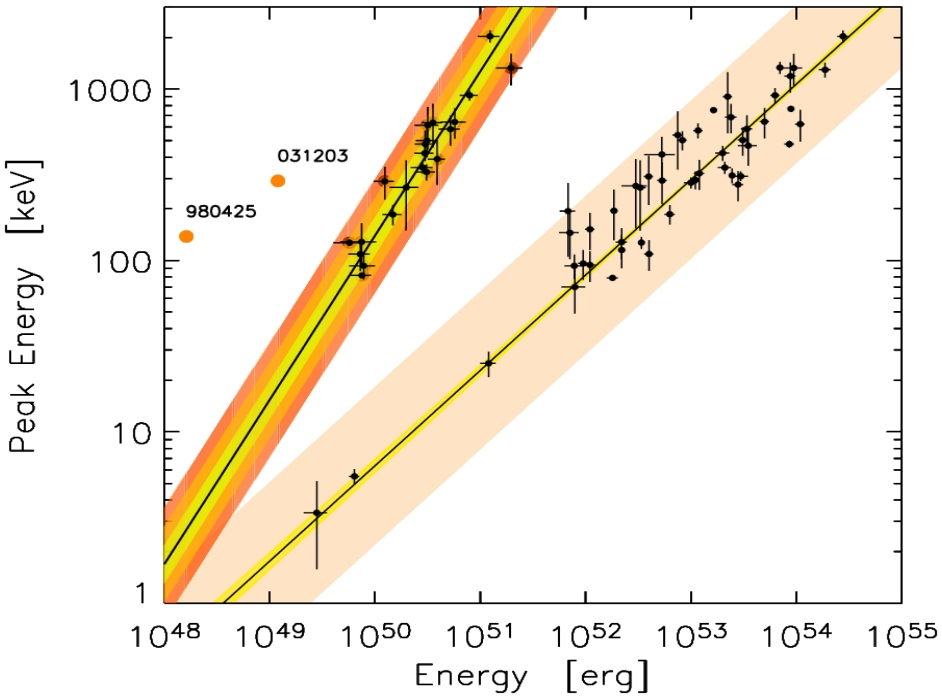
Nava et al. 2009

❑ 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)



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

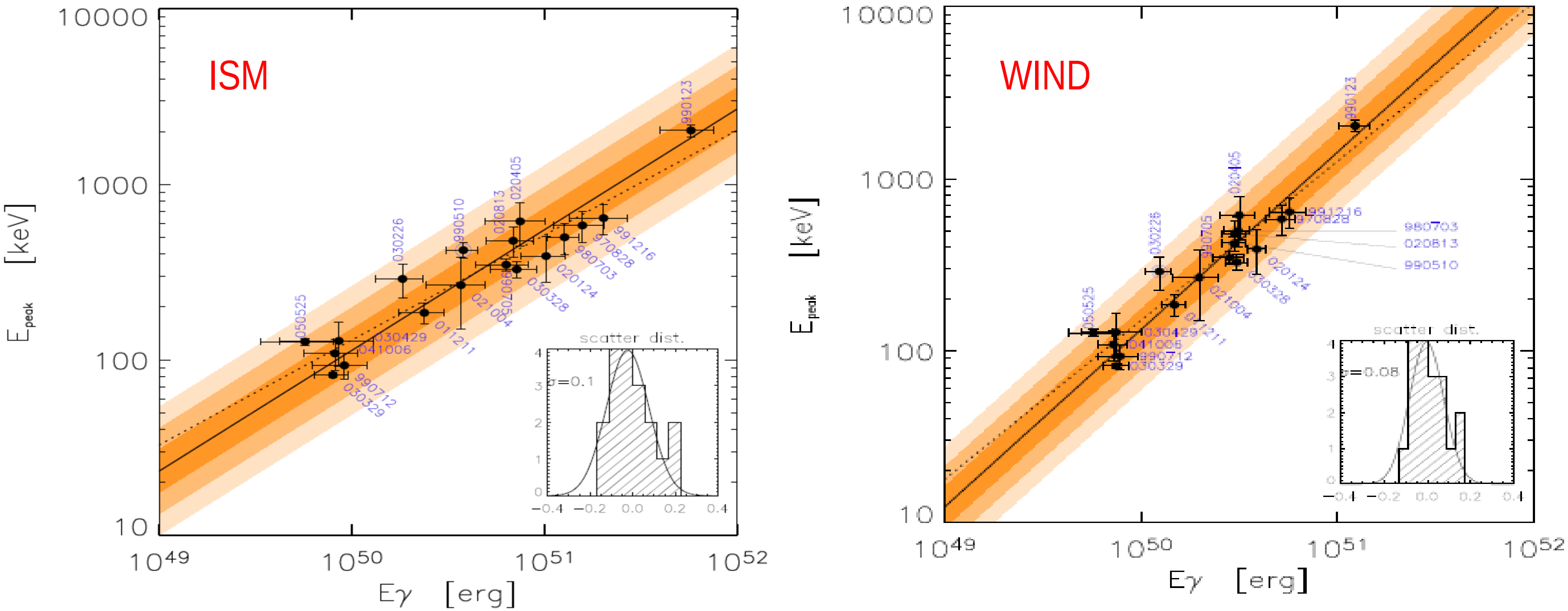
$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$



❑ BUT…

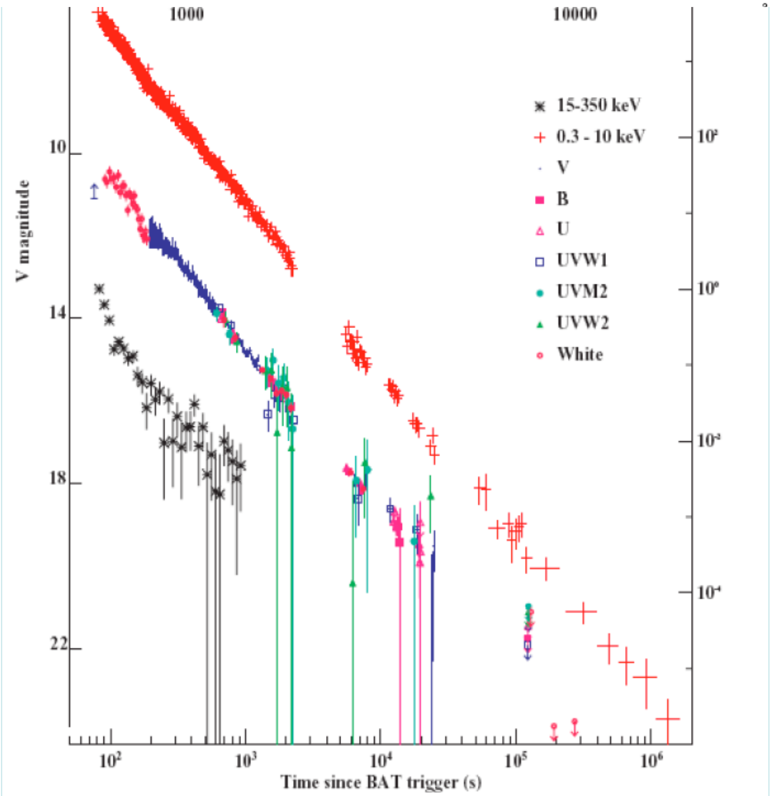
➢ the Ep-Eγ correlation is model dependent: slope depends on the assumptions on the circum-burst environment density profile (ISM or wind)

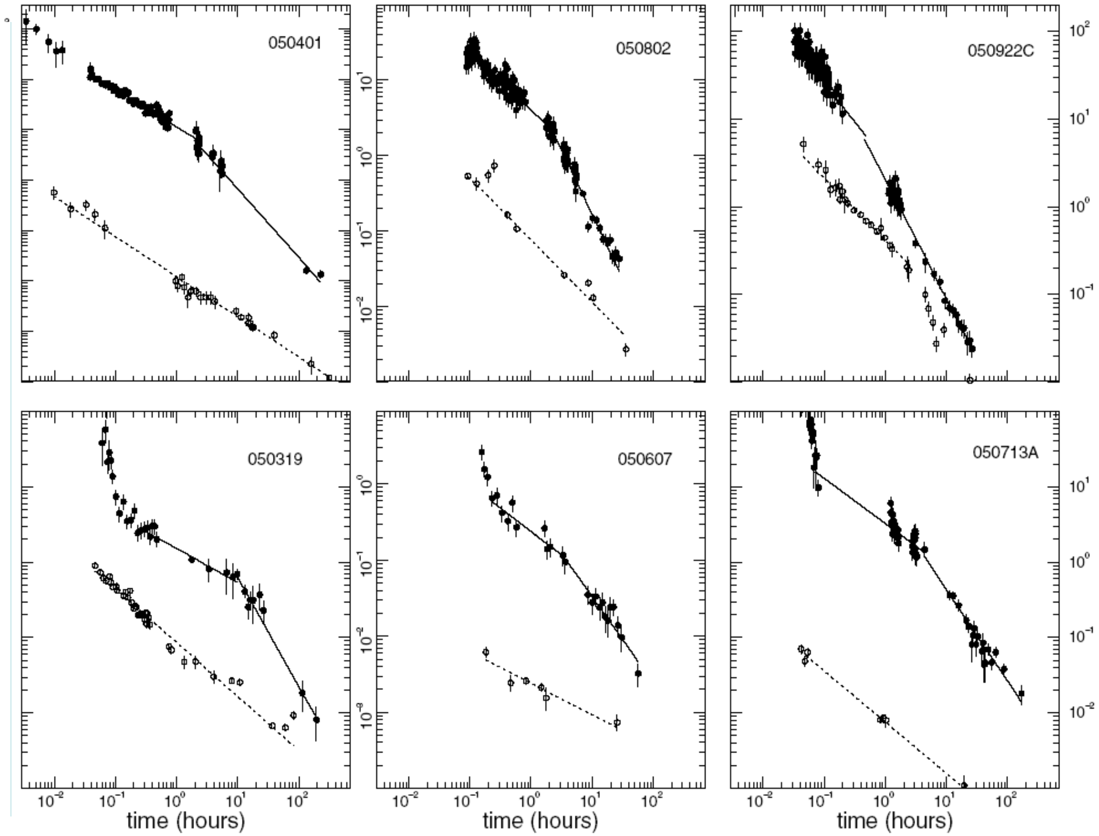
➢ addition of a third observable introduces further uncertainties (difficulties in measuring t_break, and reduces substantially the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)



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 ?





- Eiso, or the average luminosity, is the GRB brightness indicator with less systematic uncertainties

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

- addition of a third observable introduces further uncertainties (difficulties in measuring t_break, chromatic breaks, model assumptions, subjective choice of the energy band in which compute $T_{0.45}$, inhomogeneity on z of $T_{0.45}$) and substantially reduces the number of GRB that can be used (e.g., #$E_{p,i} – E_{\gamma}$ ~ ¼ #$E_{p,i} – E_{iso}$)

- recent evidences that dispersion of $E_{p,i}$-$L_{p,iso}$-$T_{0.45}$ correlation is comparable to that of $E_{p,i}$ - E_{iso} and evidences of outliers / higher dispersion of the E_p-E_{γ} and E_p-E_{iso}-t_b correlations

Conclusions and perspectives

- 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, when properly accounting for a) the dispersion of the observed correlation, b) the accuracy in the measurements, c) the impact on the estimate of Ep, fluence, Eiso of spectral model (Band, cpl) and of the combination of spectral evolution with detection/fluence thresholds, there is no firm evidence of significant selection / instrumental effects.

- The existence of the Ep,i(t) – Liso(t) correlation within single GRBs, confirmed by Fermi data, cannot be explained by selection effects and 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 focus should be in better estimating the true dispersion and identifying the best intensity indicator (Eiso, Liso, Lp,iso, coll. corectect quantities) or a combination of them.

- 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