Cosmology with Gamma-Ray Bursts: status and perspectives

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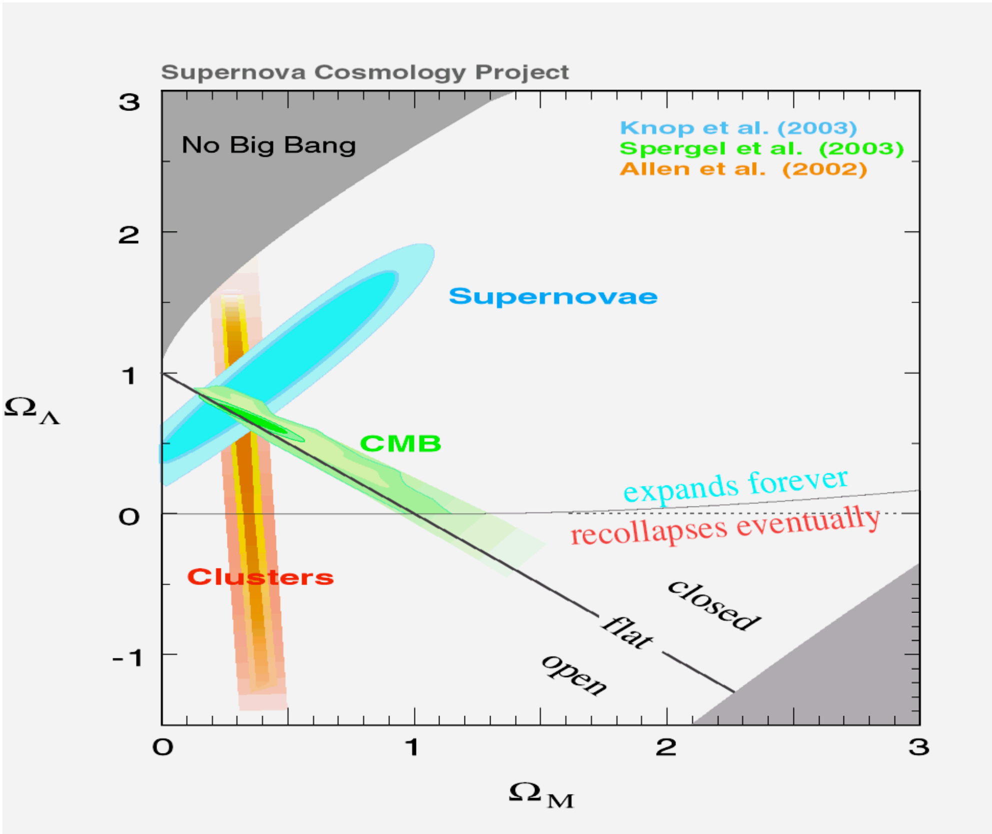
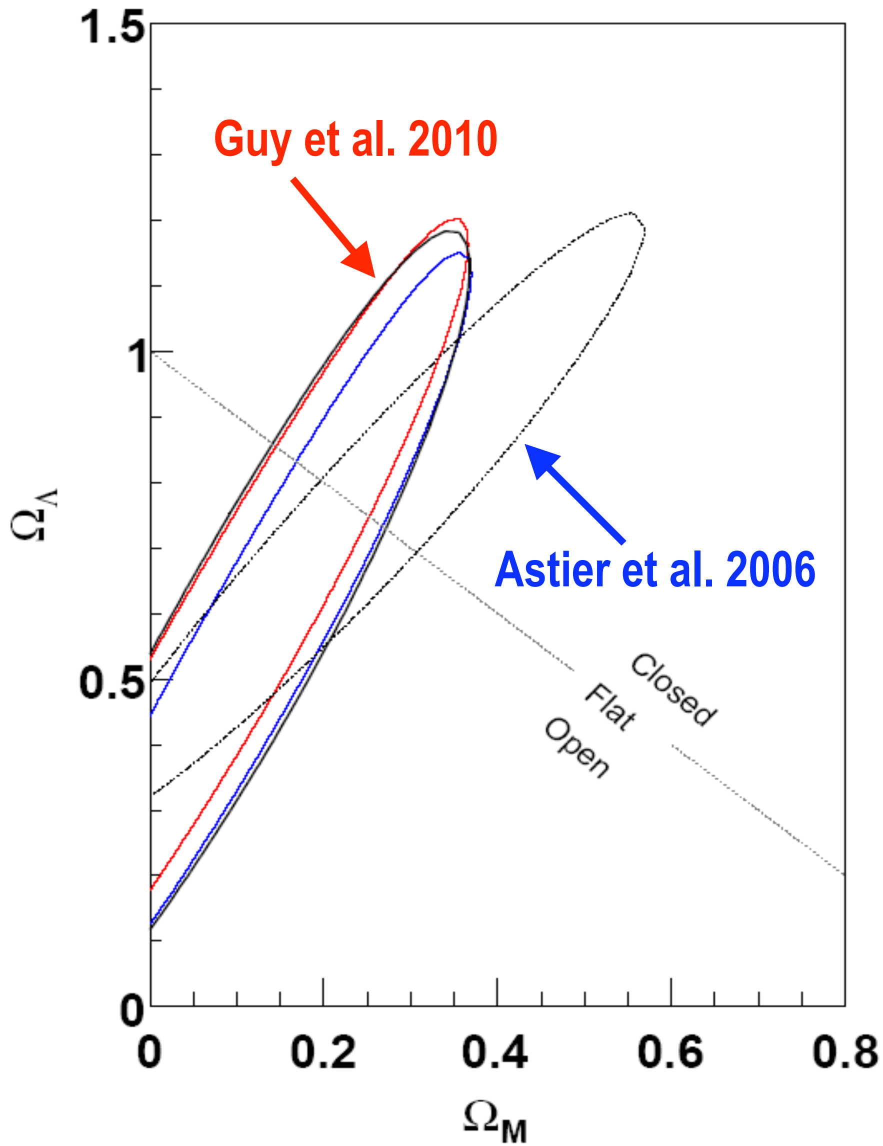
First National Meeting on Science and Technology with SKA
The Italian pathway to SKA

Why looking for more cosmological probes ?

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



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



Recent results from SNLS (231 SNe Ia at 0.15 < z < 1.1, Guy et al. 2010) compared to those of Astier et al. 2006 (44 low redshift SNe along with the 71 SNe from the SNLS first year sample)

❑ Each cosmological probe is characterized by possible systematics

❑ e.g SN Ia:

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

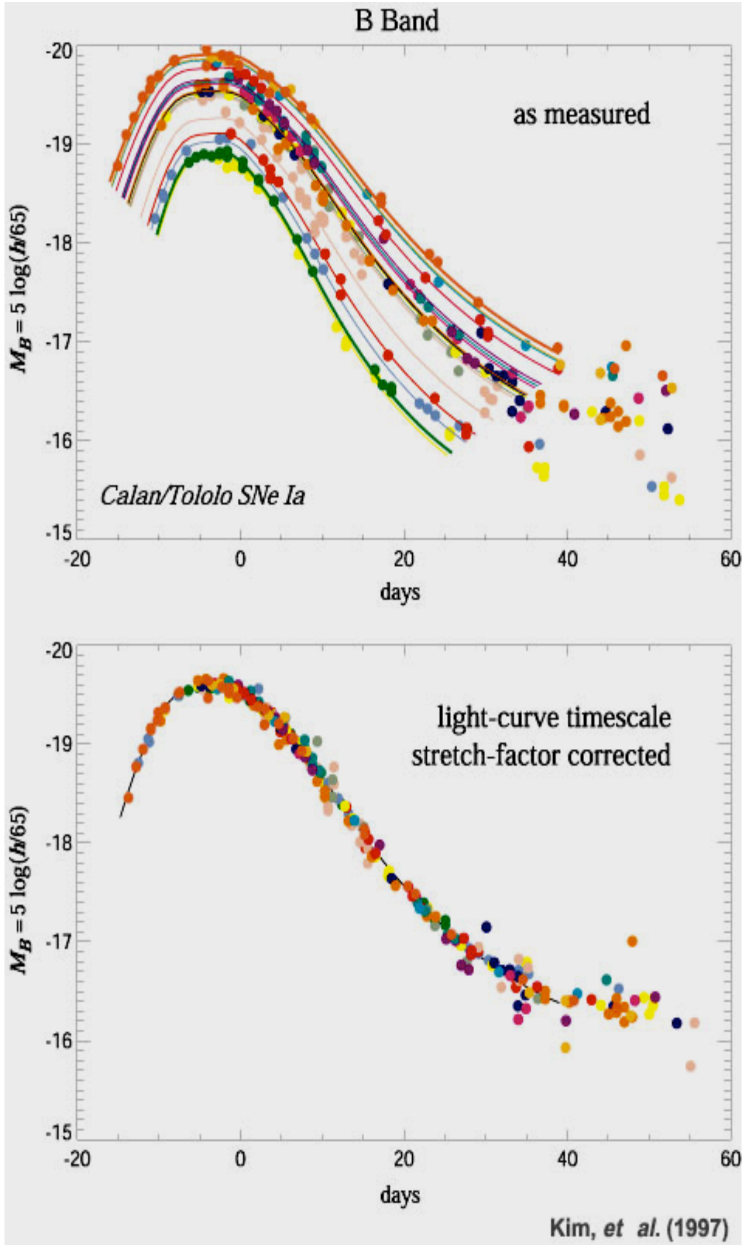
➢ light curve shape correction for the luminosity normalisation may depend on z

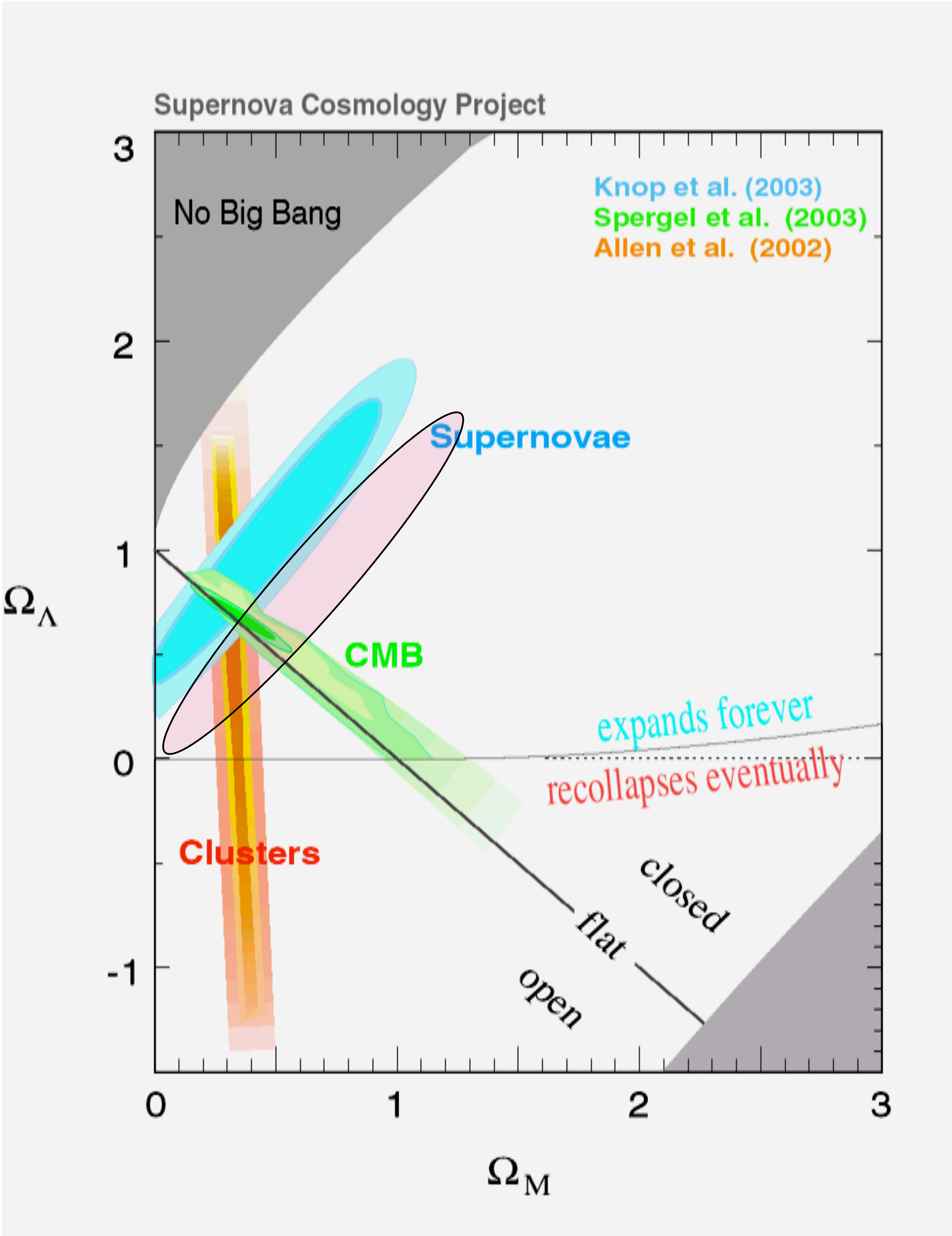
➢ signatures of evolution in the colours

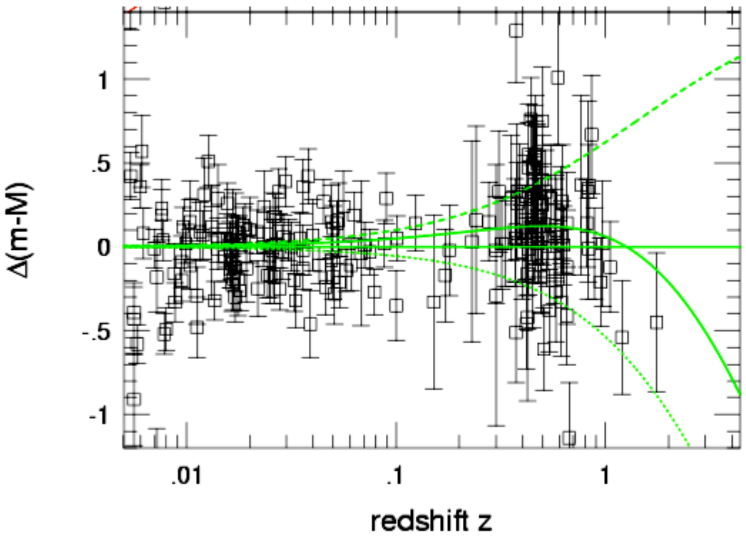
➢ correction for dust extinction

➢ anomalous luminosity-color relation

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





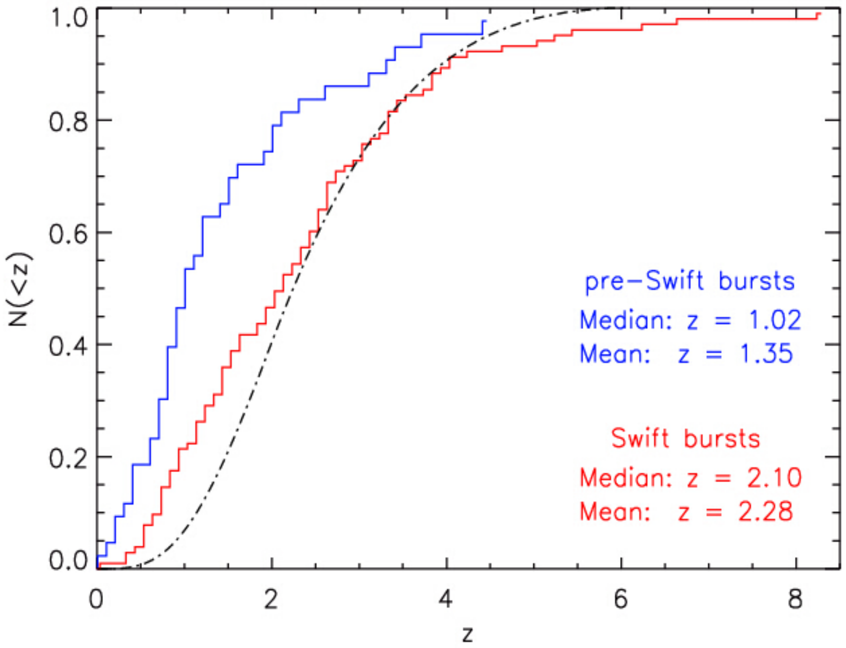


If the "offset from the truth" is just 0.1 mag….

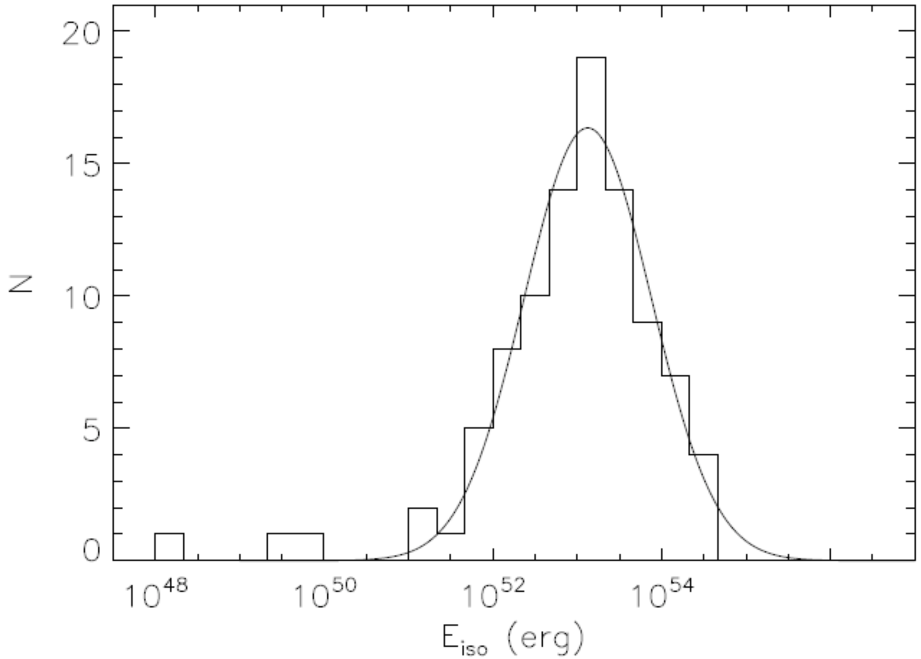
(slide by M. della Valle)

Are GRB standard candles ?

- all GRBs with measured redshift (~250, including a few short GRBs) lie at cosmological distances (z = 0.033 – ~9.4) (except for the peculiar GRB980425, z=0.0085)
- isotropic luminosities and radiated energy are huge and span several orders of magnitude: **GRB are not standard candles (unfortunately)**



Jakobsson, 2009

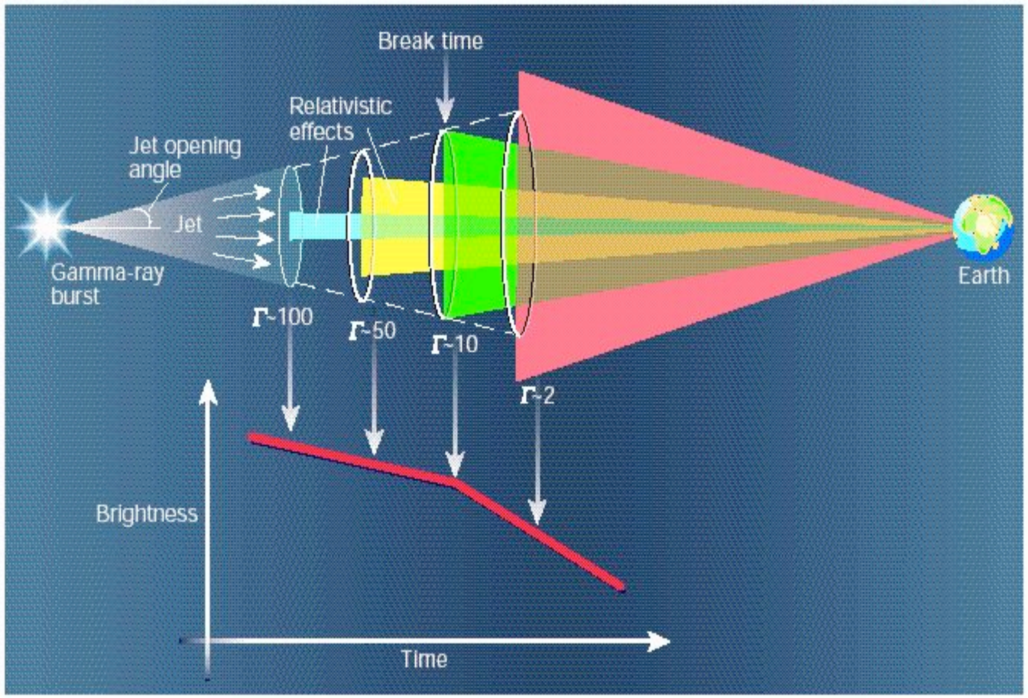


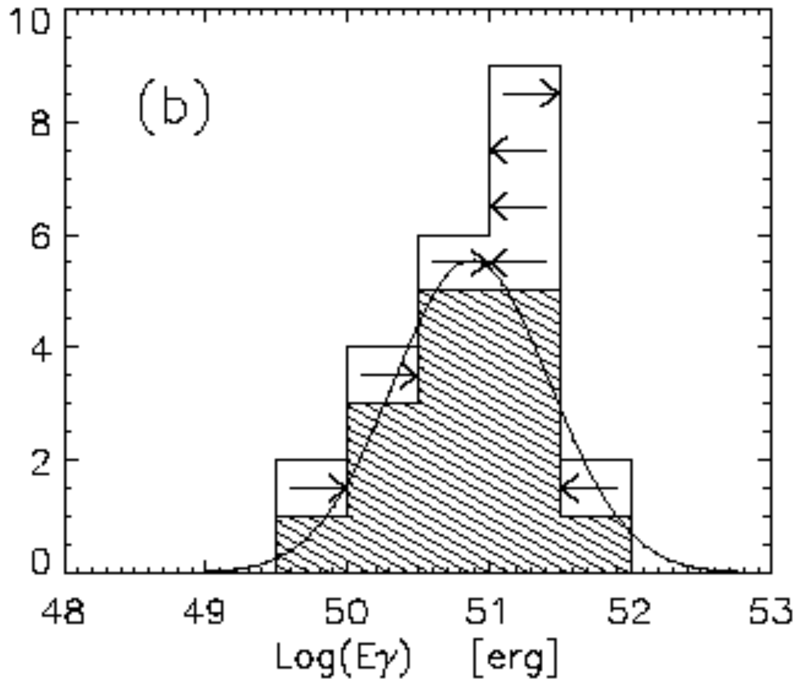
Amati, 2009

- jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, 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**

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

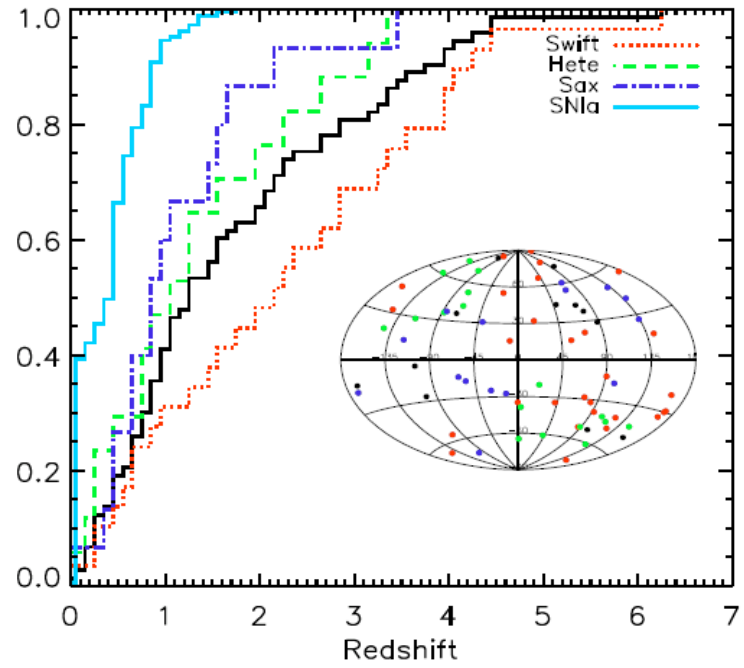
$$E_\gamma = (1-\cos\theta)E_{\gamma,iso}.$$

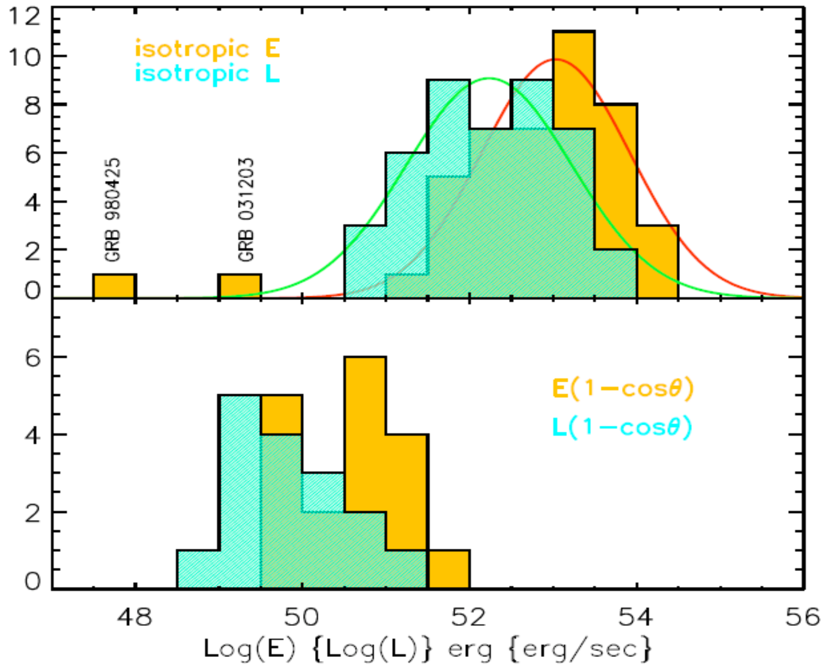


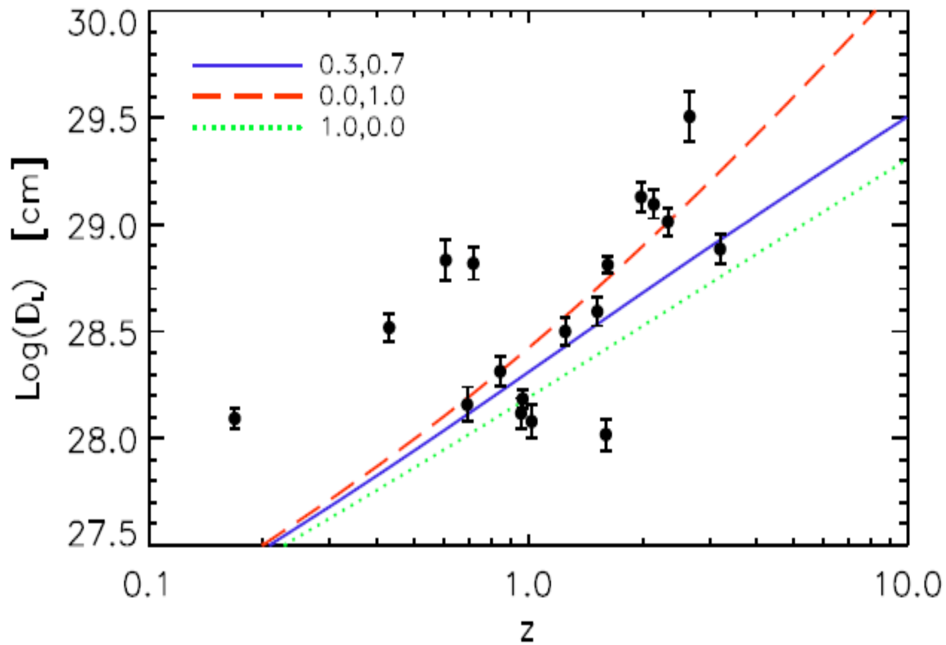


Ghirlanda et al., 2004

- GRB have huge luminosity, a redshift distribution extending far beyond SN Ia
- high energy emission -> no extinction problems

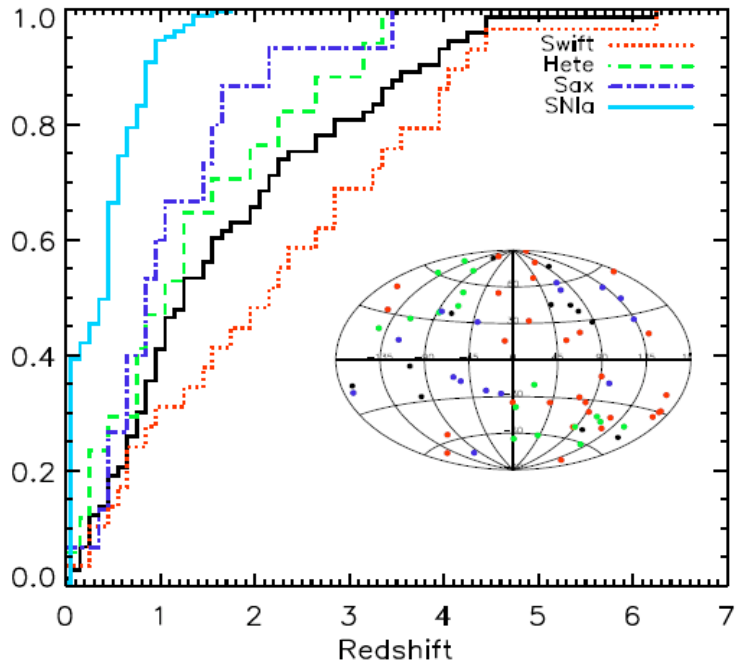


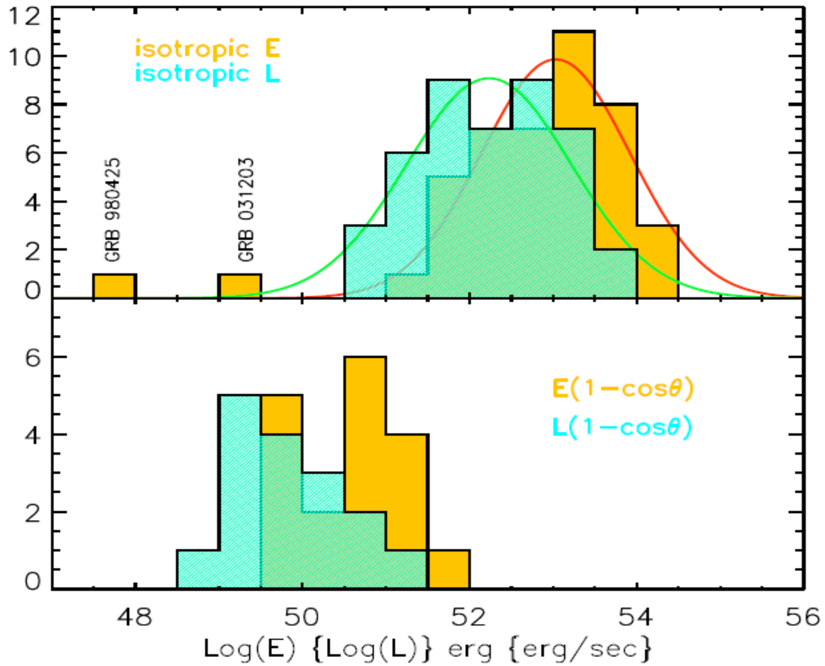


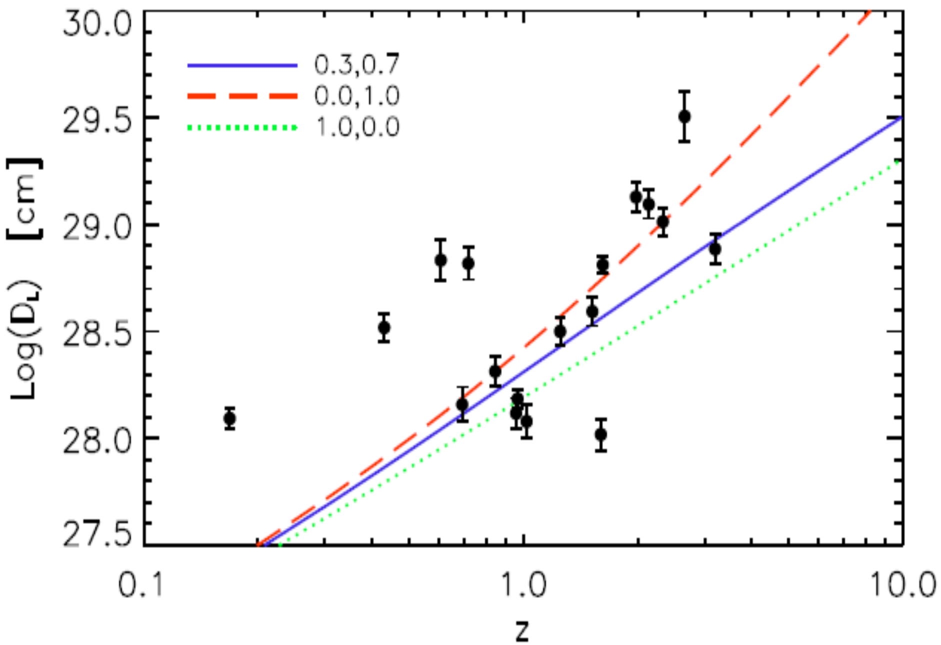


Ghirlanda et al, 2006

- 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

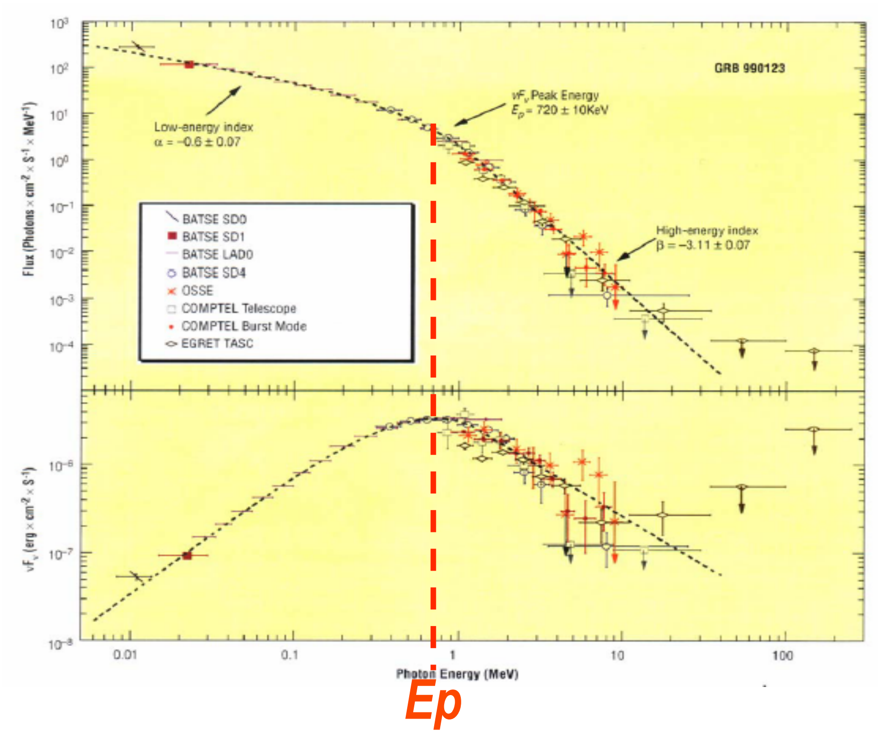
The Ep,i – Eiso correlation

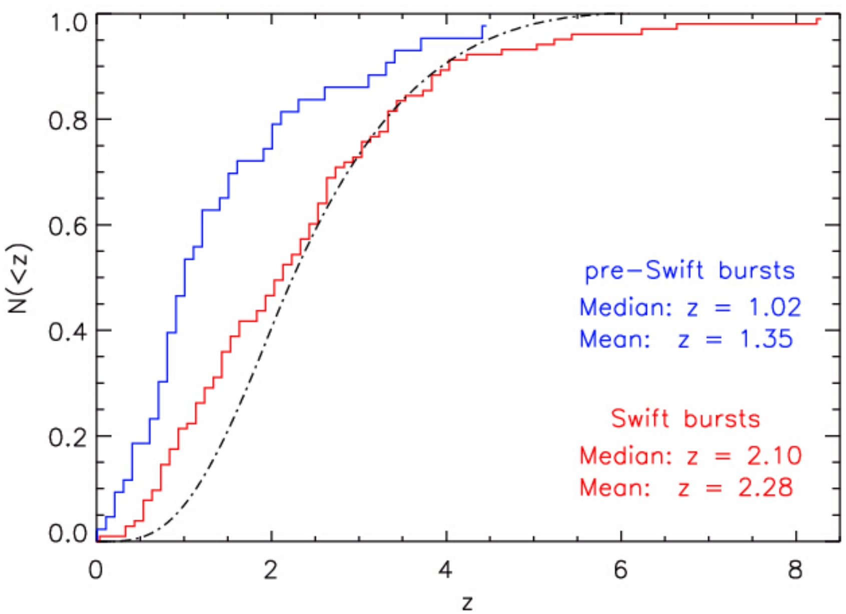
- GRB spectra typically described by the empirical Band function with parameters α= low-energy index, β= high-energy index, E_0=break energy

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

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

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

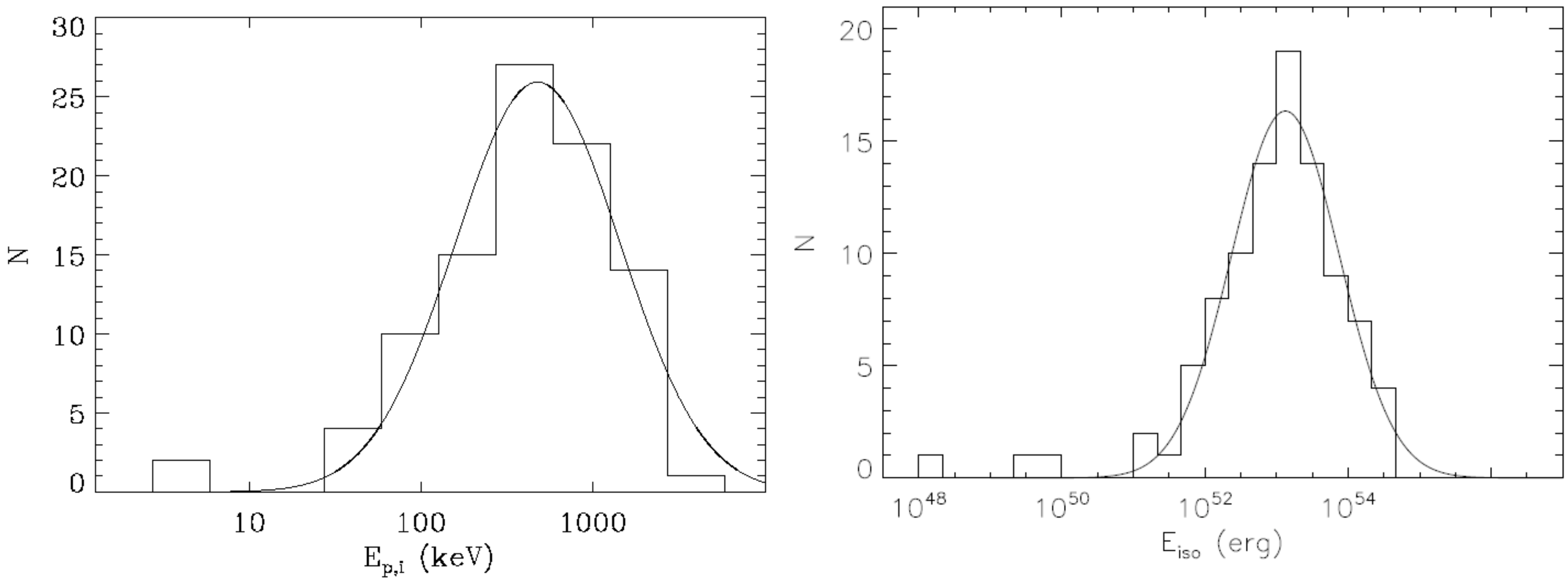




Jakobsson (2009)

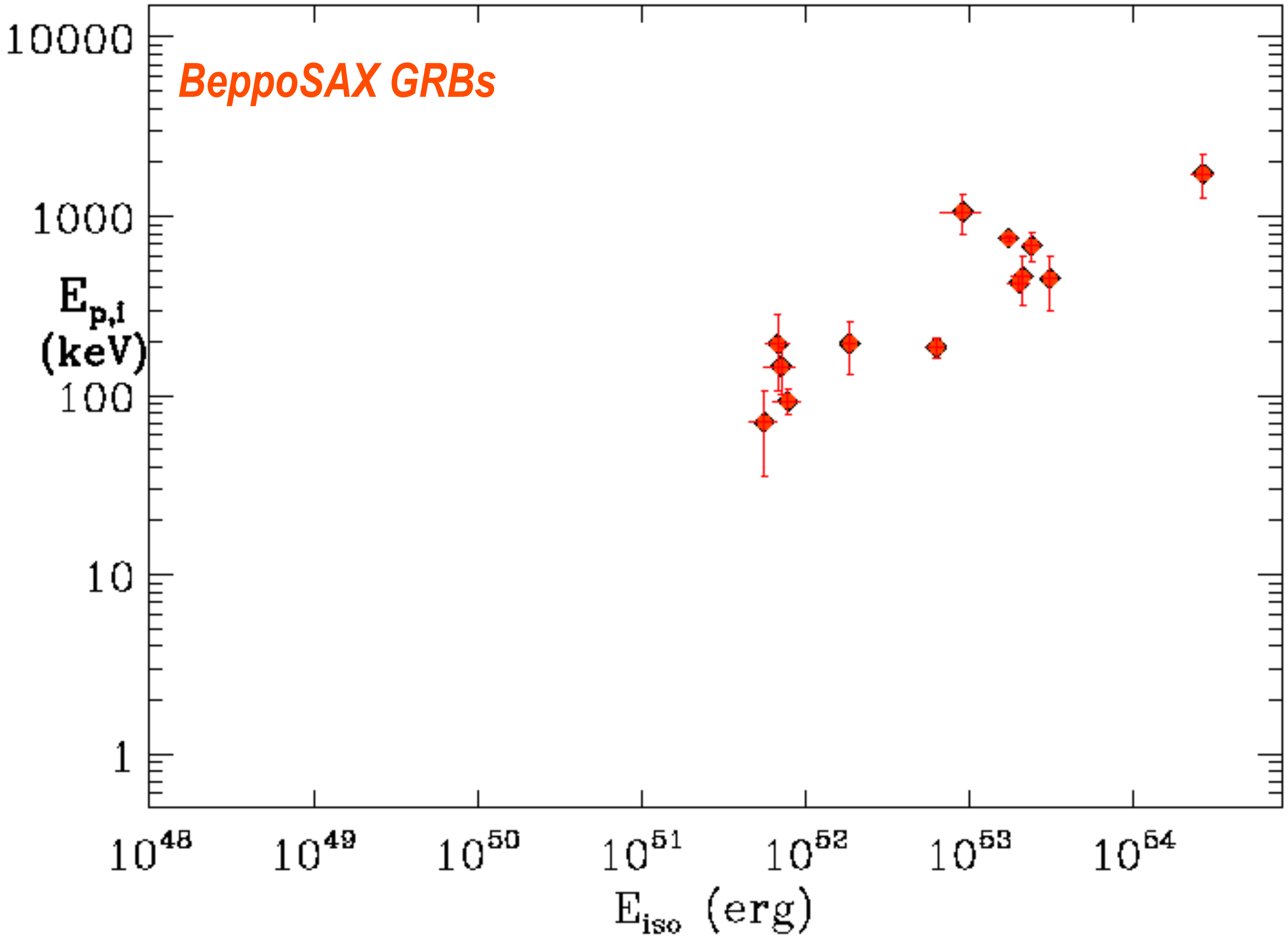
➢ ~260 GRBs with measured redshift, about 50% have measured spectra

➢ 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)



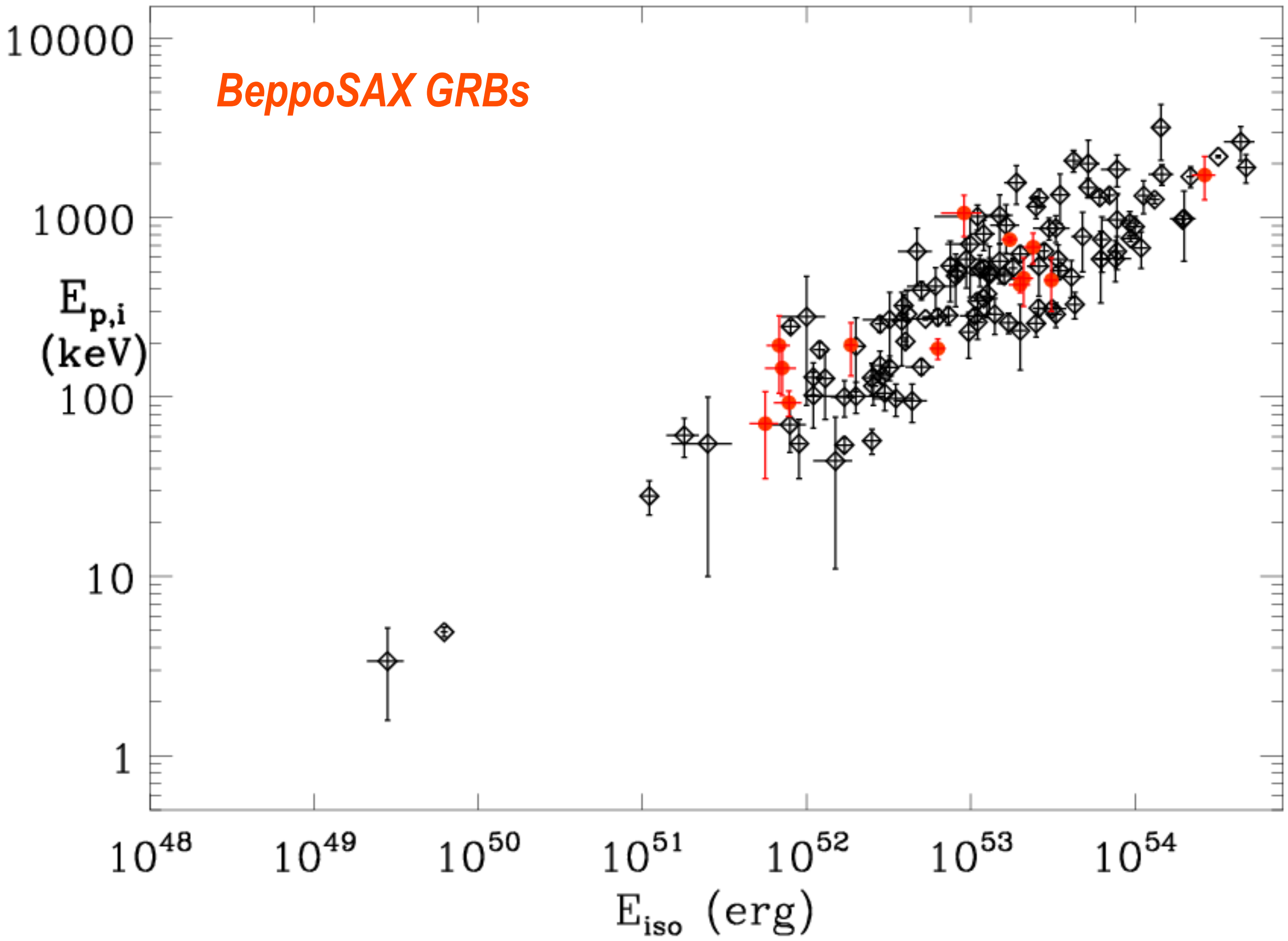
95 GRBs, sample of Amati, Frontera & Guidorzi, A&A (2009)

➢ 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



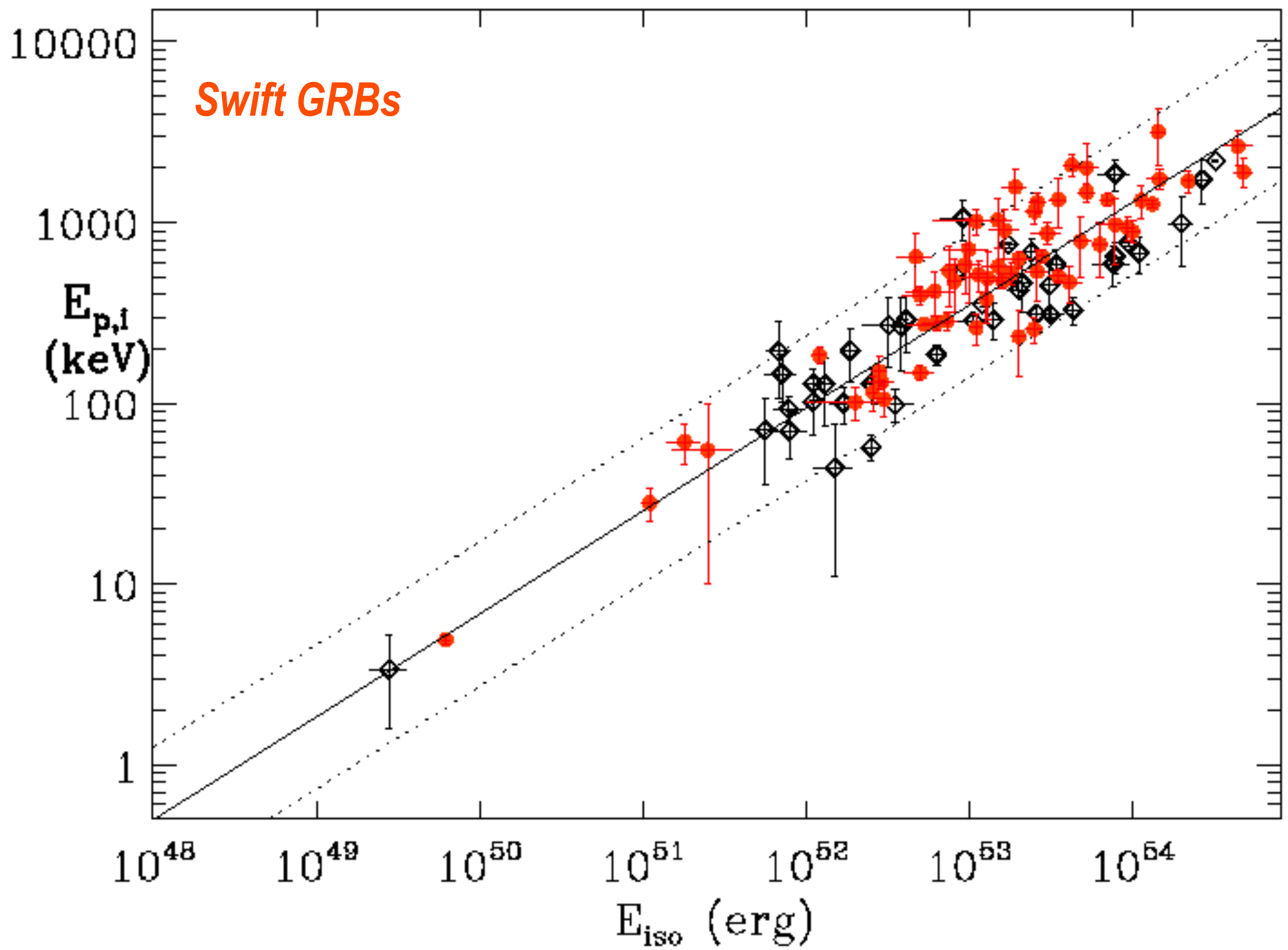
➢ Ep,i – Eiso correlation for GRBs with known redshift confirmed and extended by measurements of ALL other GRB detectors with spectral capabilities

130 long GRBs as of Sept. 2011



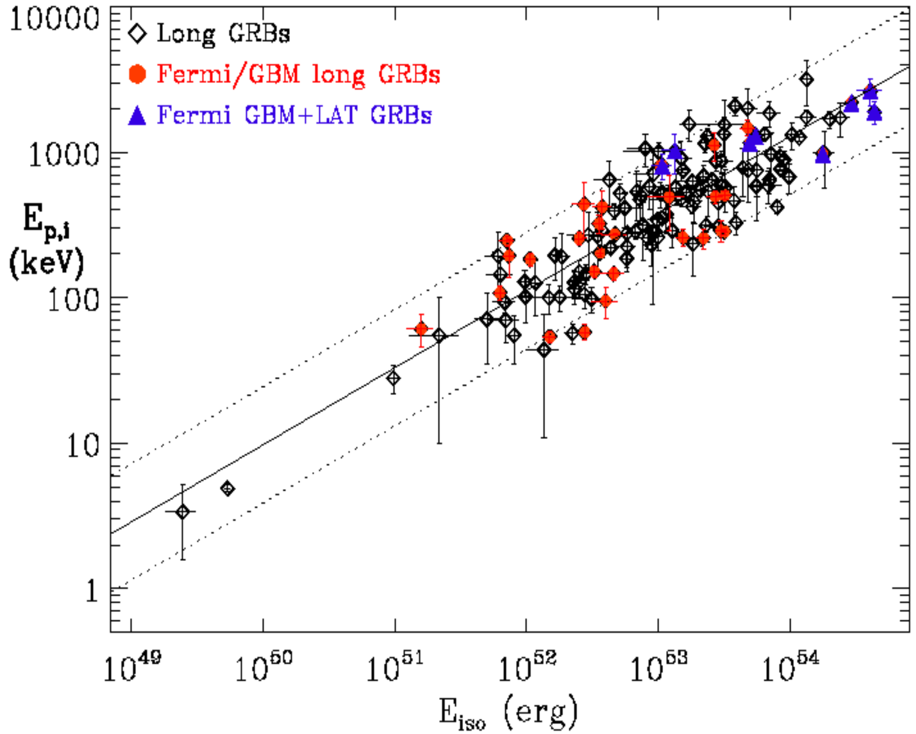
➢ Swift: reduction of selection effects in redshift

➢Ep,i of **Swift GRBs measured** by Konus-WIND, Suzaku/WAM, Fermi/GBM and BAT (values provided by the Swift/BAT team (GCNs or Sakamoto et al. 2008).

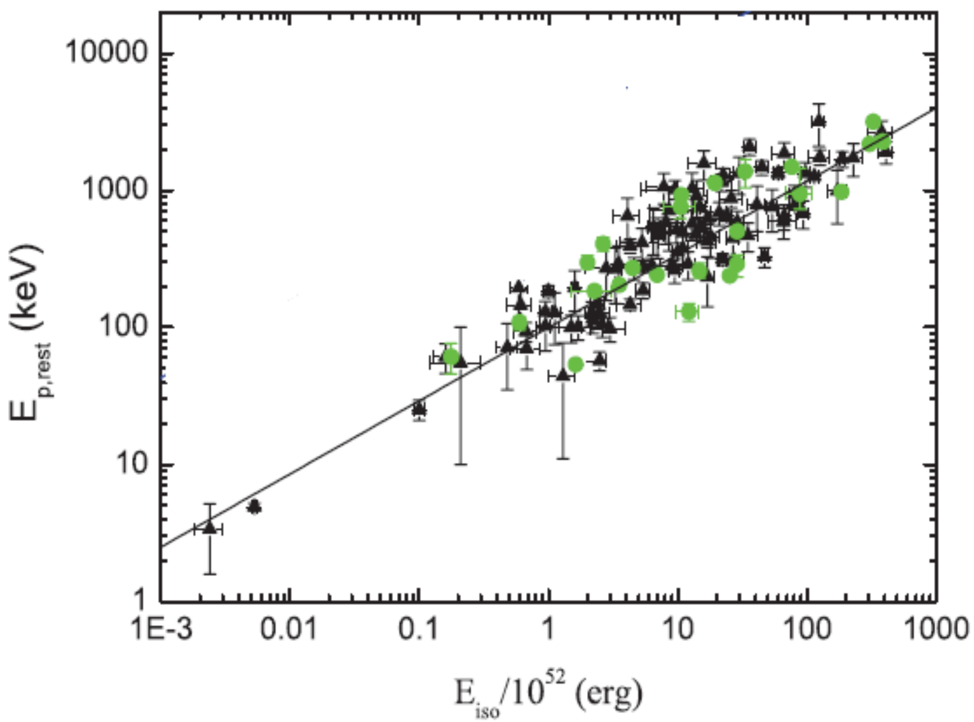


❑ Fermi: unprecedentred broad-band coverage of prompt emission (~10 keV – GeV) – reduction of biases in measurement of Ep

❑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

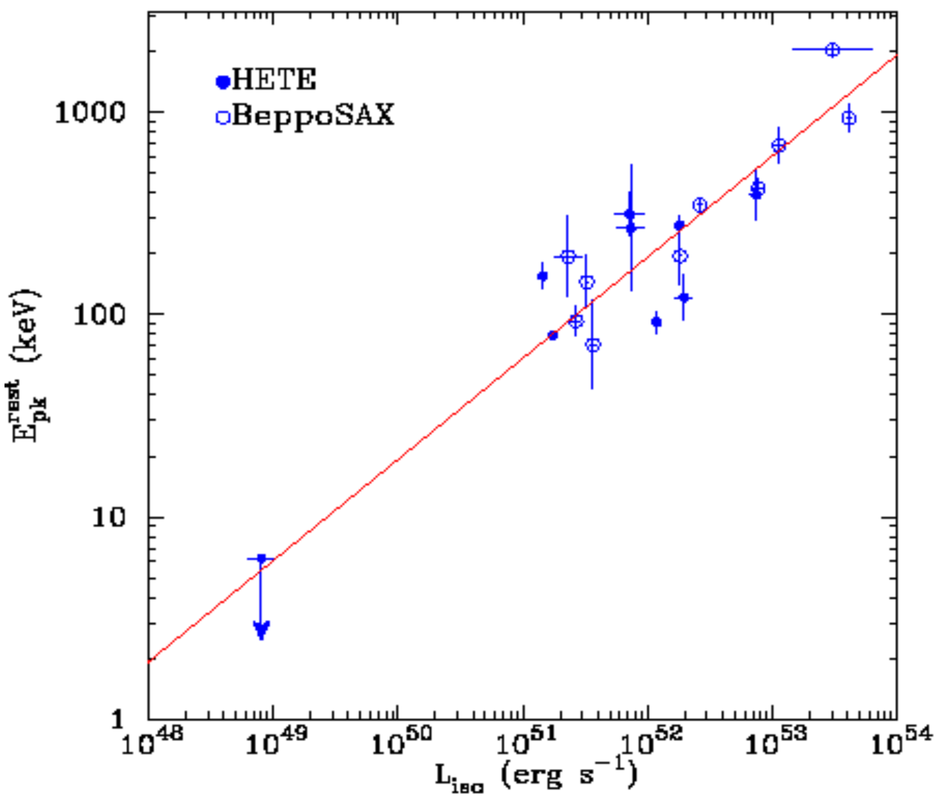


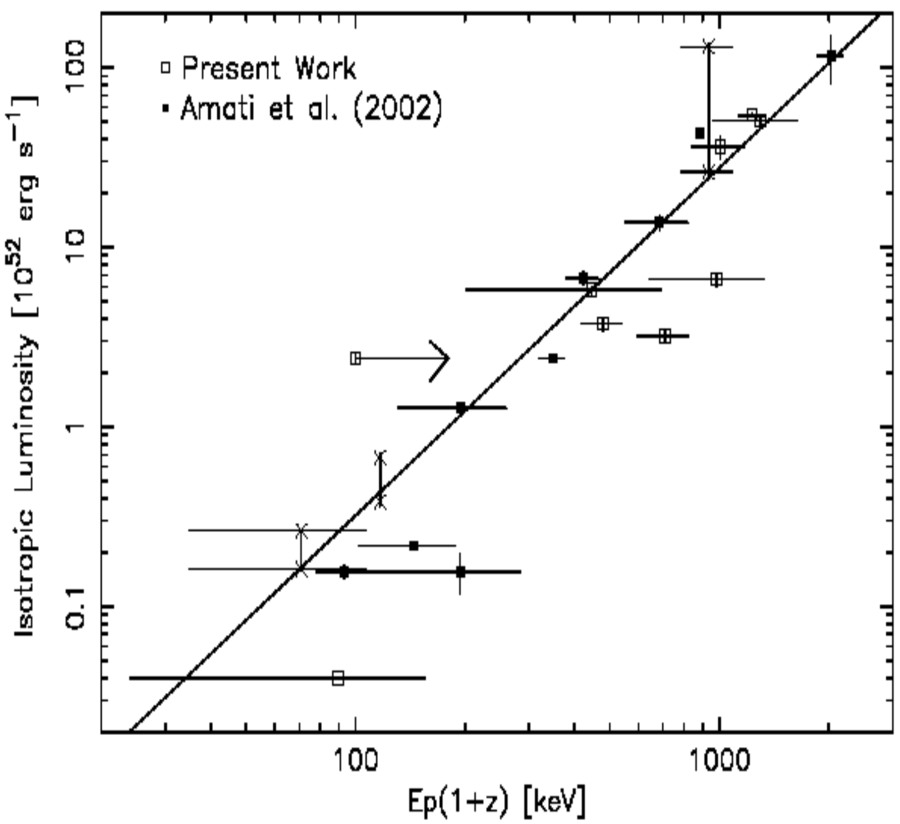
Zhang et al. 2012

➢ 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)

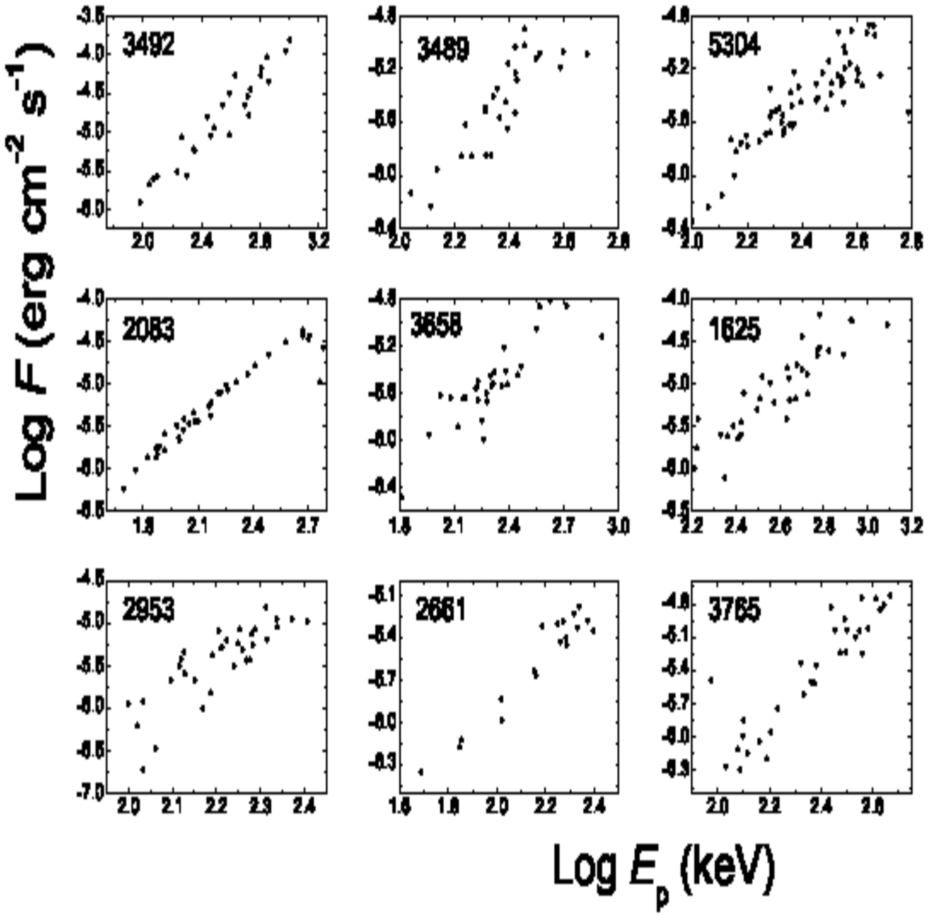
➢ this is expected because Liso and Lpeak,iso are strongly correlated with Eiso

➢ w/r to Eiso, Liso and Lp,iso are more difficult to estimate and subject to larger uncertainties

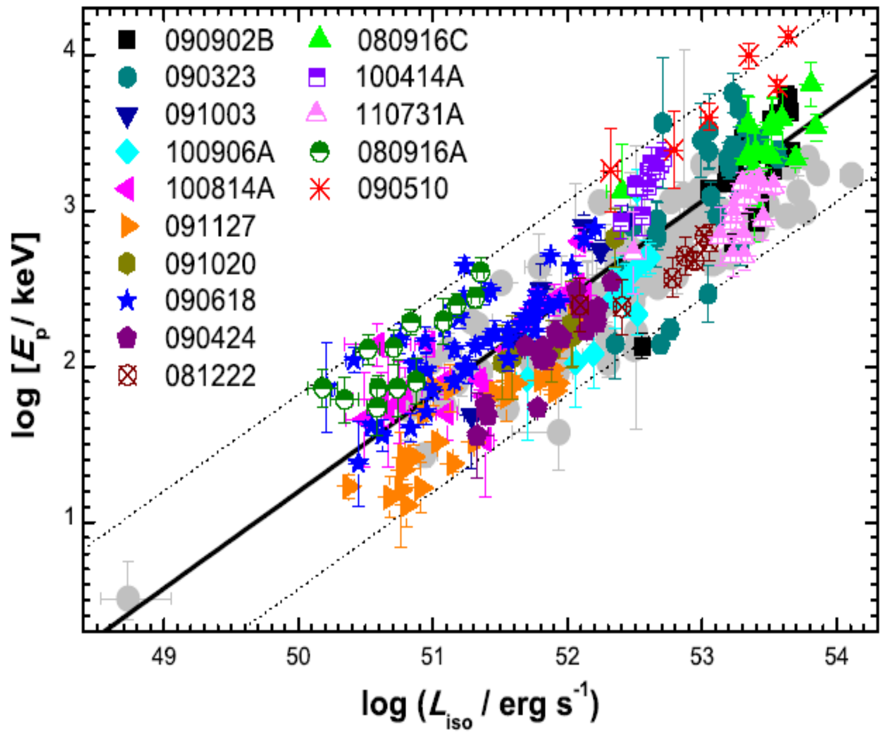




➢ the Ep,i– Liso correlation holds also within a good fraction of GRBs (Liang et al. 2004, Firmani et al. 2008, Frontera et al. 2012, Ghirlanda et al. 2009): **robust evidence for a physical origin and clues to explanation**

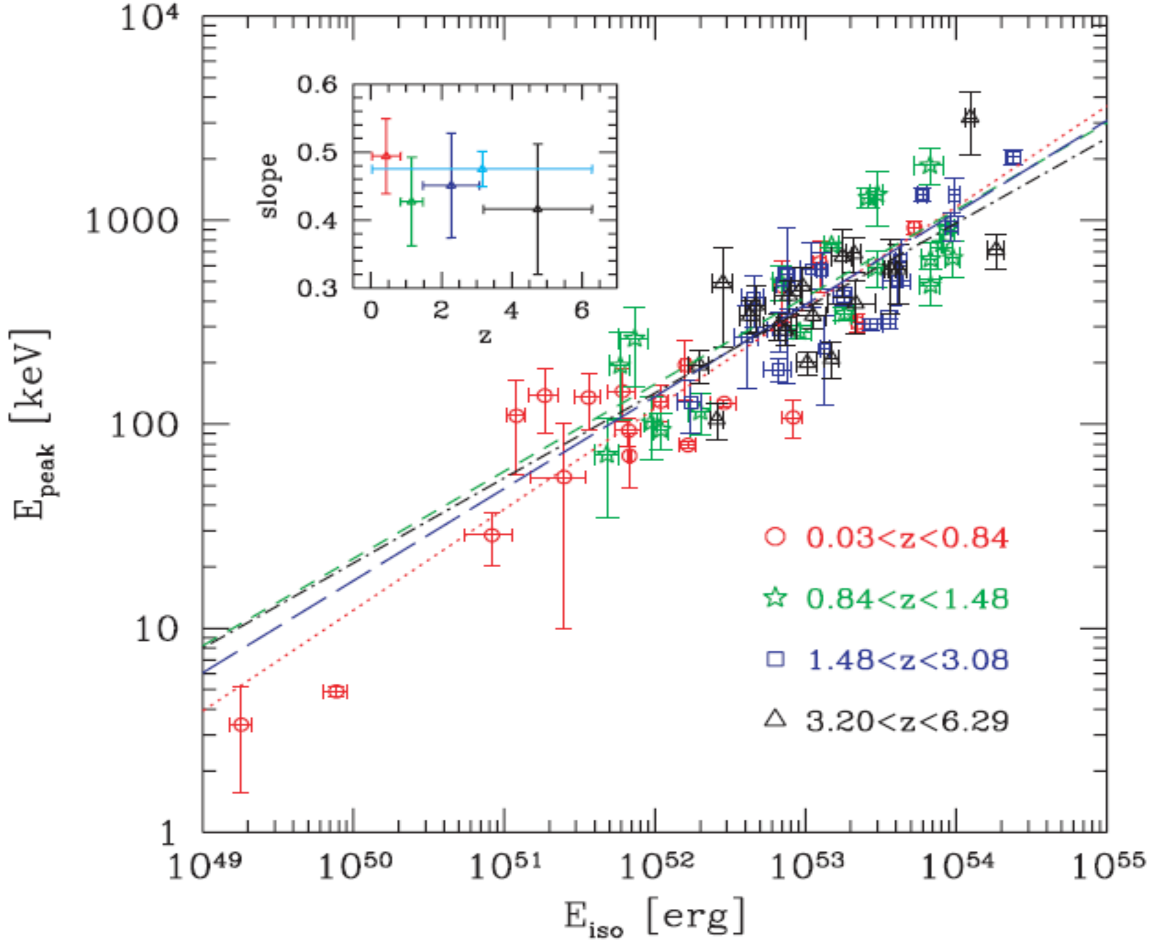


BATSE (Liang et al., ApJ, 2004)



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

❑ No evidence of evolution of index and normalization of the Ep,i – Eiso correlation with redshift



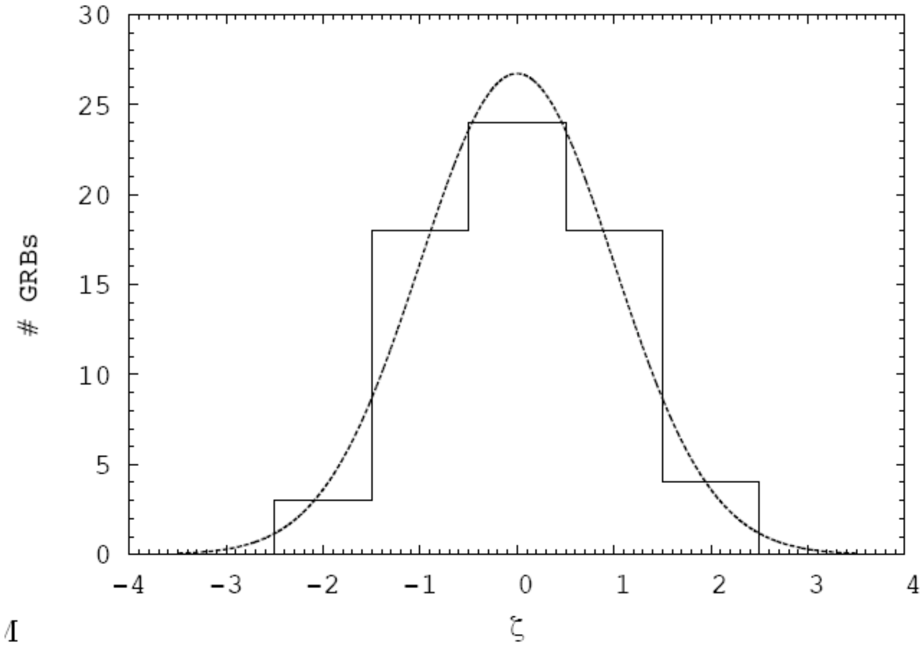
Ghirlanda et al. 2008

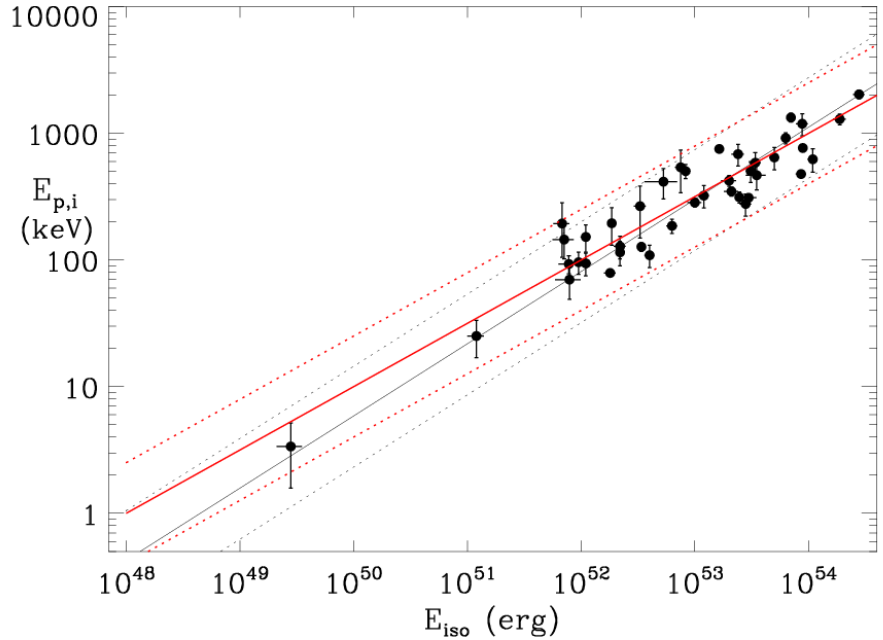
➢ strong correlation but significant dispersion of the data around the best-fit power-law; the distribution of the residuals can be fit with a Gaussian with σ(logEp,i) ~ 0.2

➢ the "extra-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

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

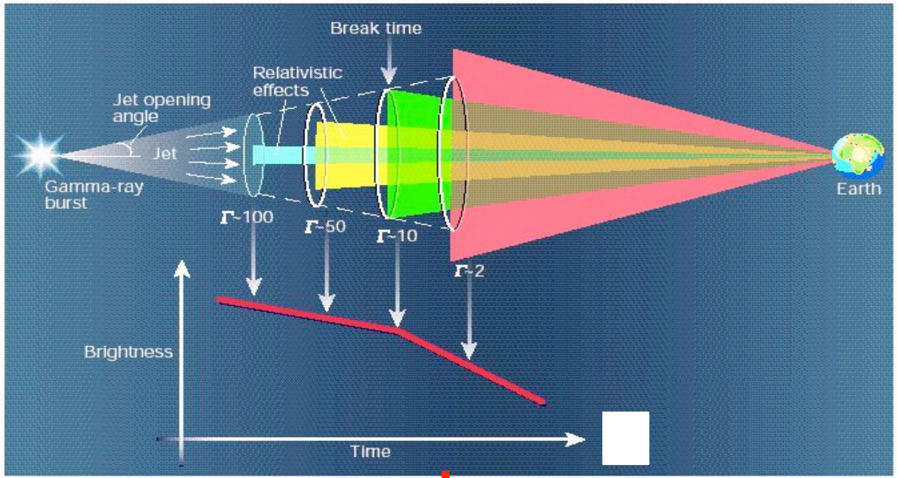
➢ with this method Amati et al. (2008, 2009) found an extrinsic scatter σ_{int}(logEp,i) ~ 0.18 and index and normalization t ~0.5 and ~100, respectively





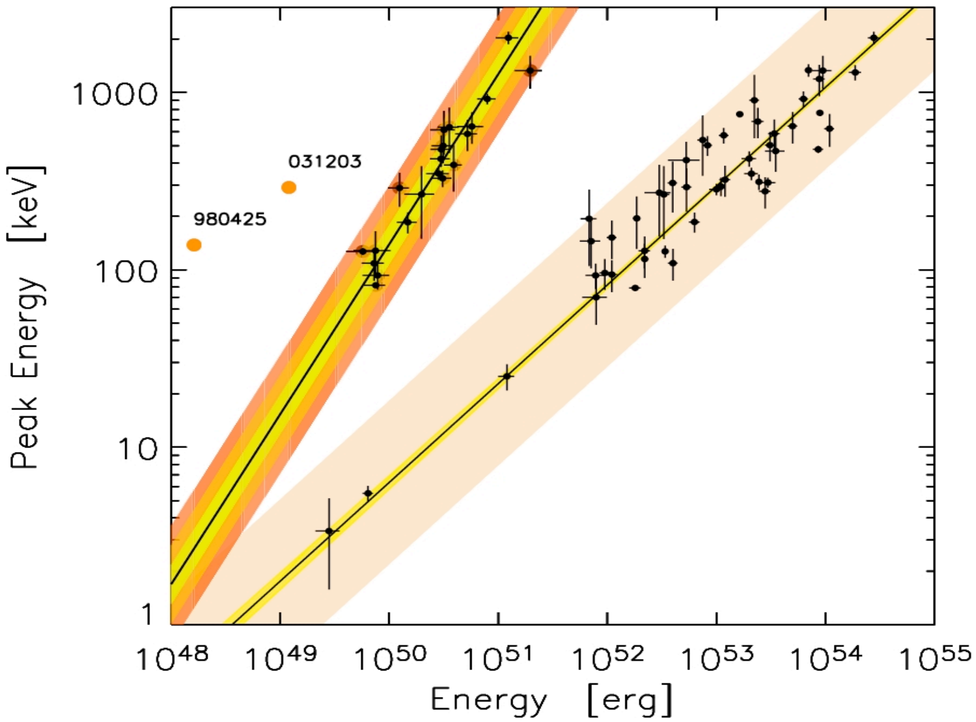
"Standardizing" GRB with Ep,i-brightness correlations

❑ 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)



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

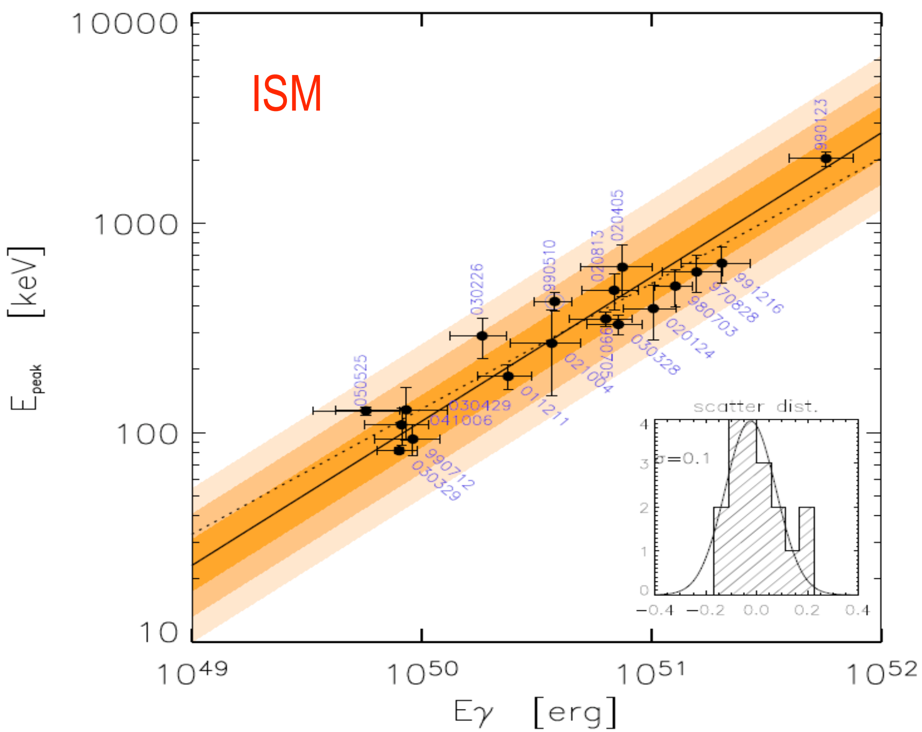
$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$

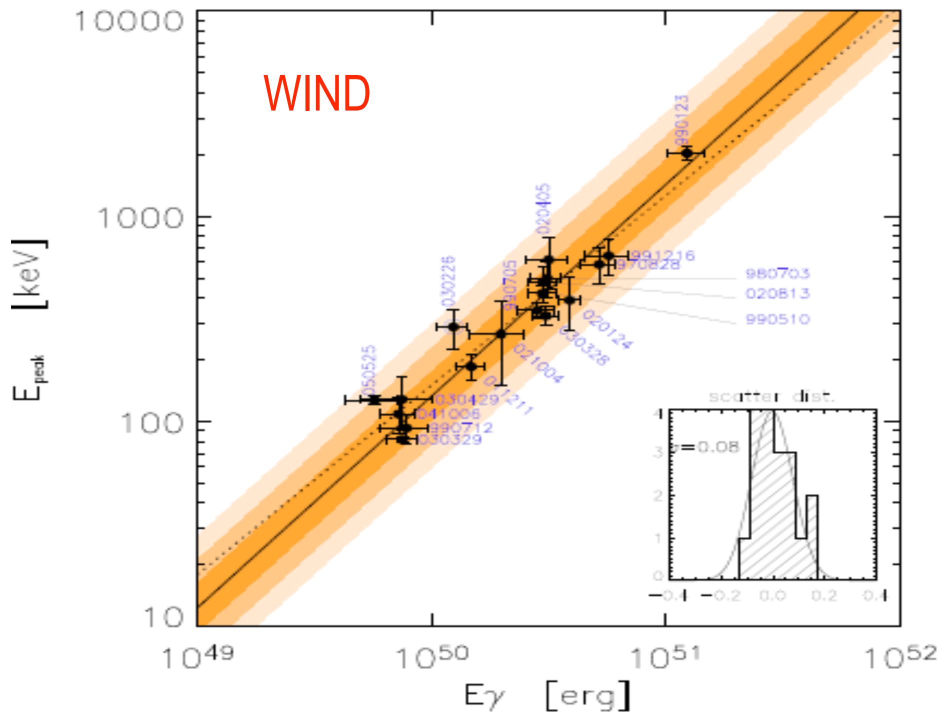


❑ BUT…

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

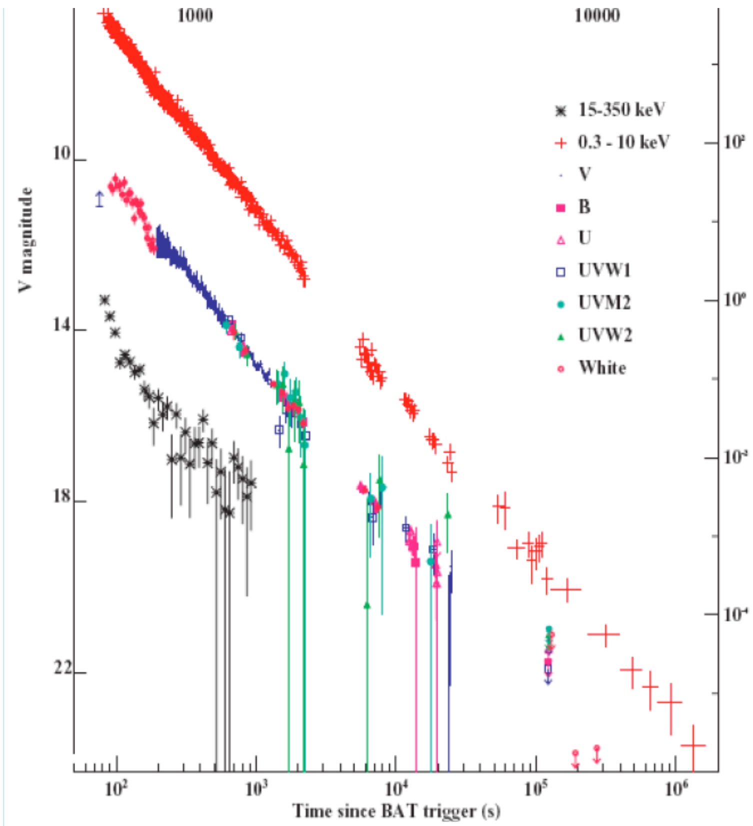
➢ **addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions, subjective choice of the energy band in which compute T0.45, inhomogeneity on z of T0.45) and substantially reduces the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)

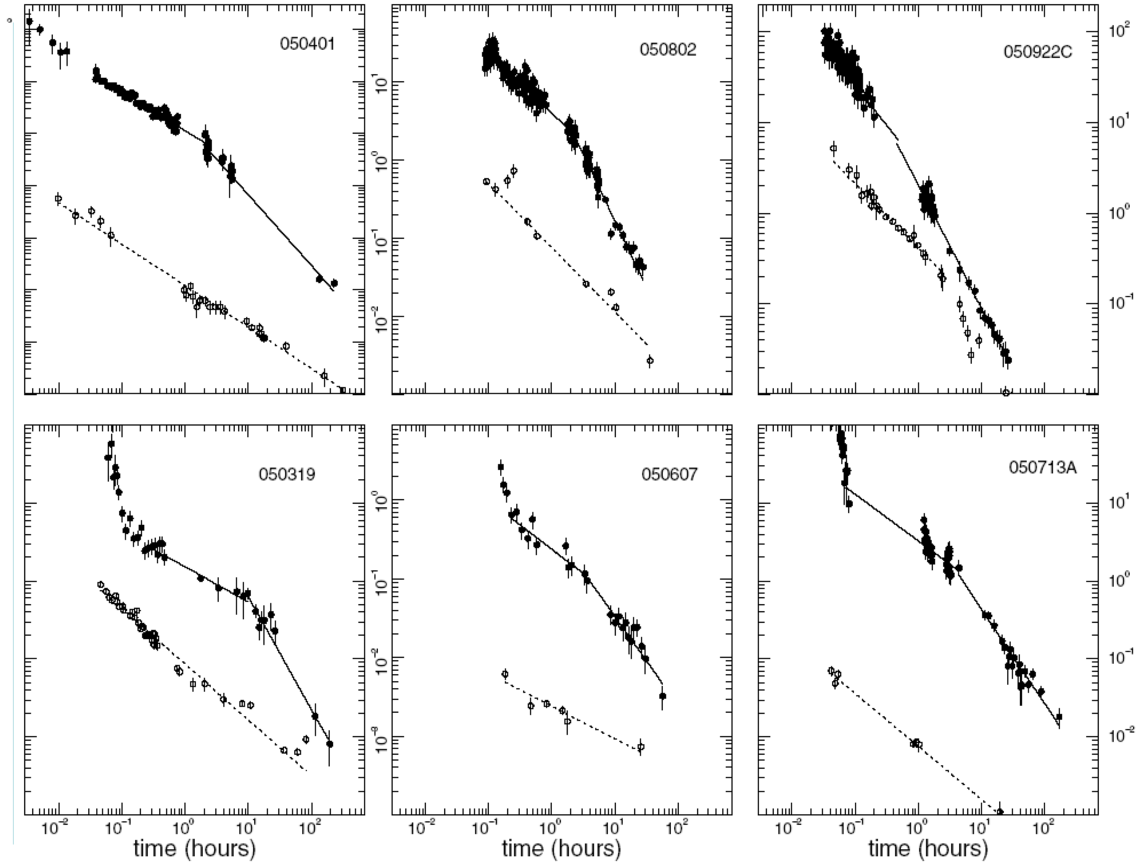




Nava et al.. , A&A, 2005: ISM (left) and WIND (right)

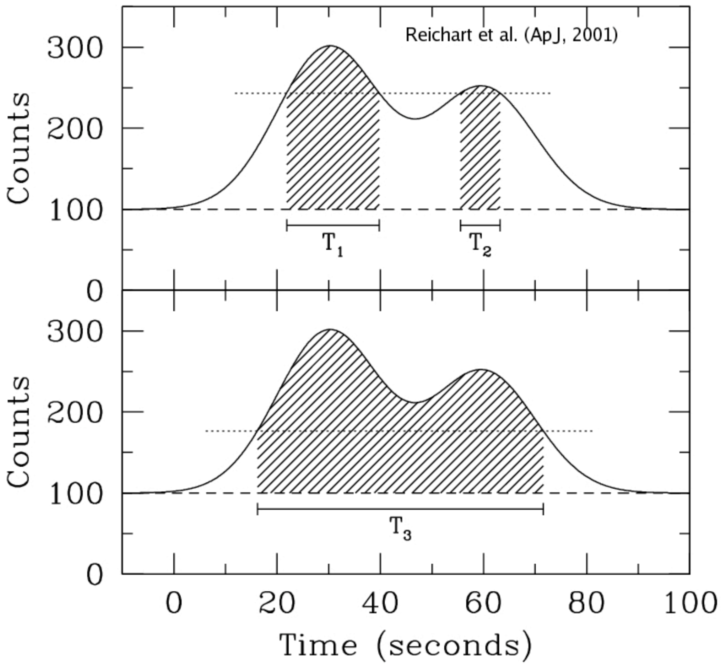
- lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break
- challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory modeling of jets ?

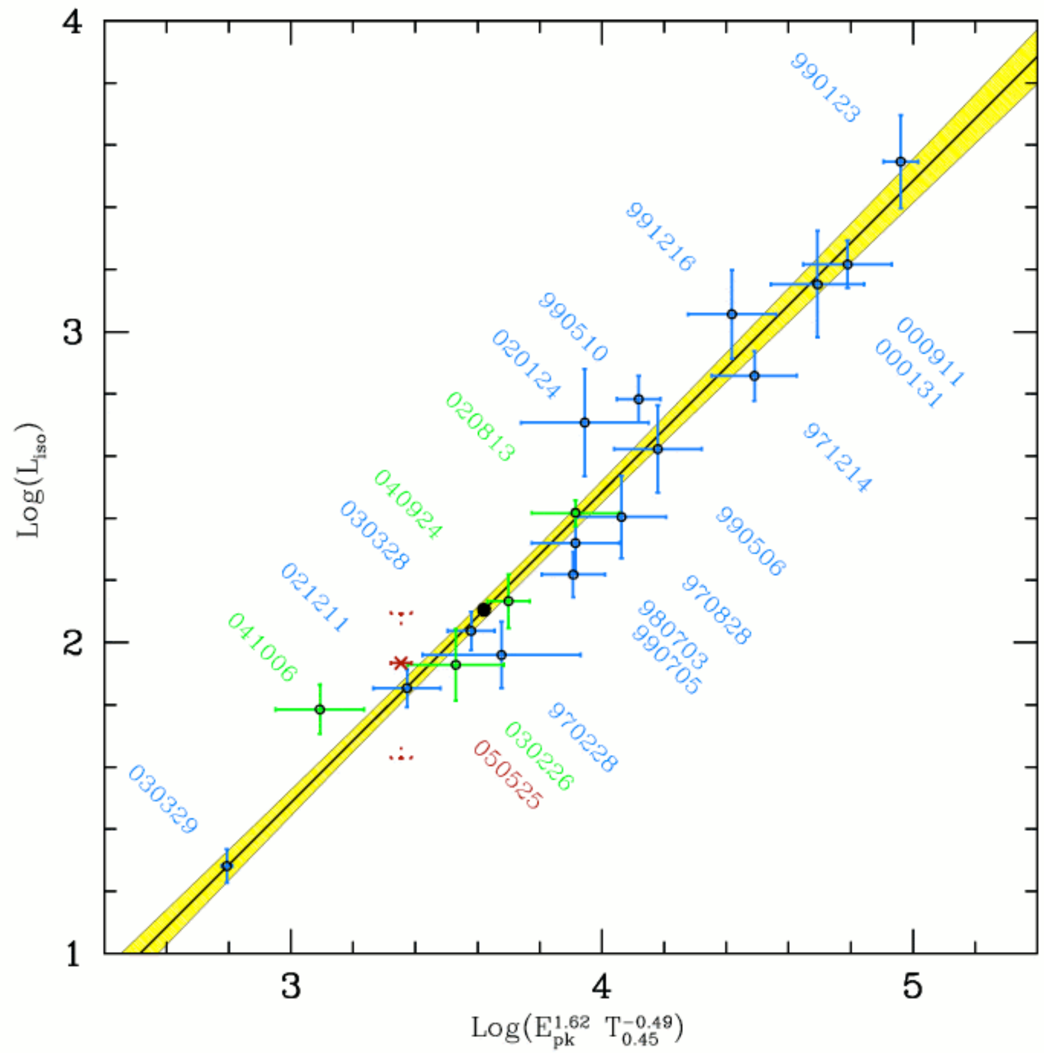




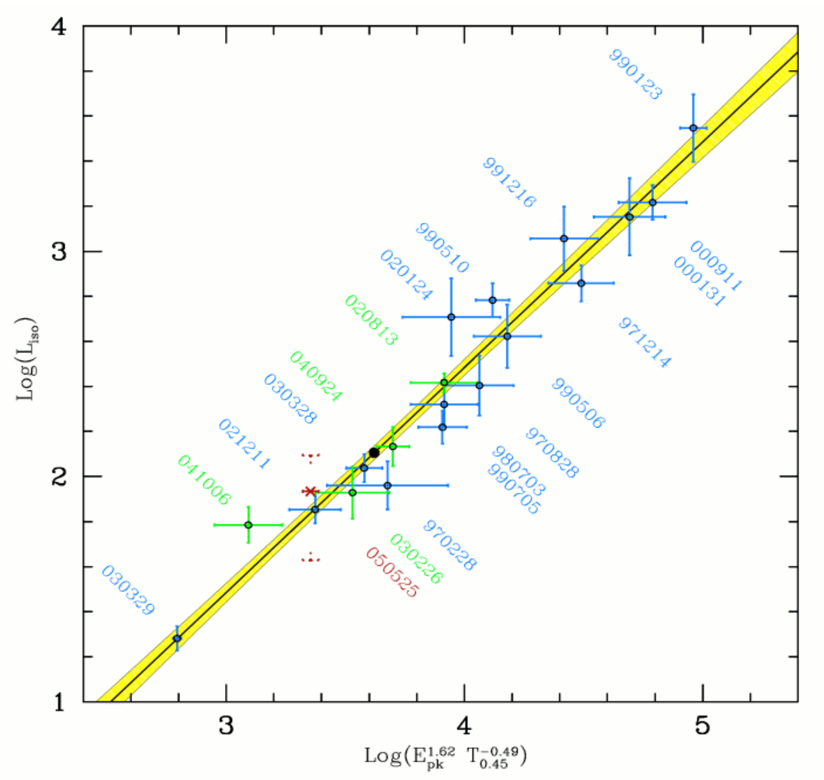
❑ A tight correlation between Ep,i, Lpeak,iso and time scale $T_{0.45}$ was also claimed, based on still small number of events and proposed for standardizing GRBs (Firmani et al. 2006 and others)

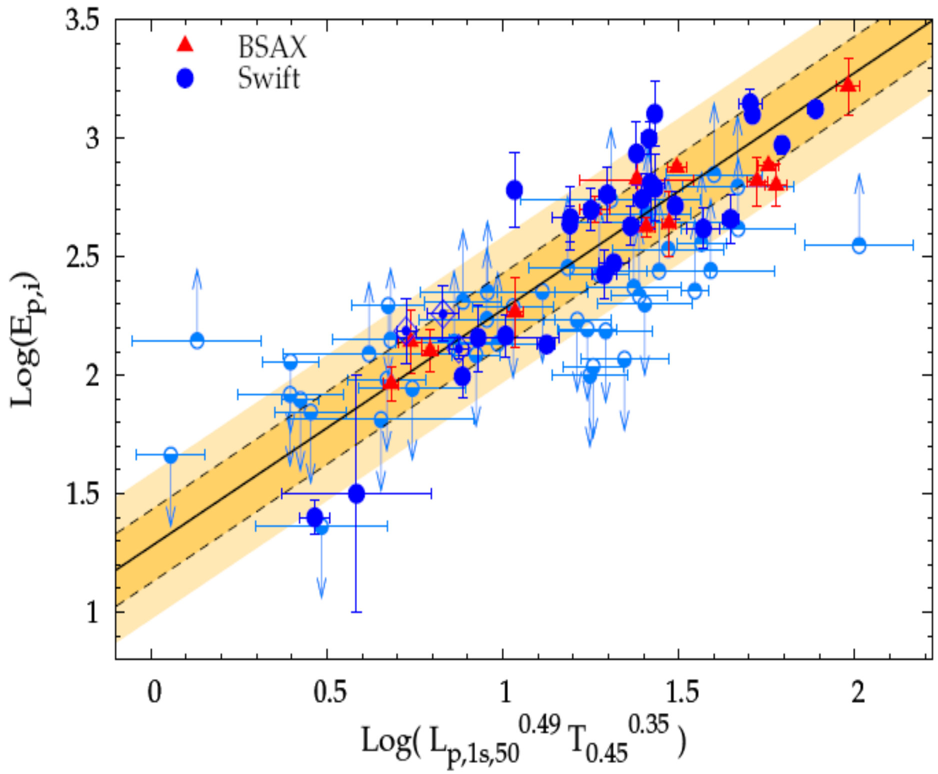
$$L_{\rm iso} \propto E_{\rm pk}^{1.62} T_{0.45}^{-0.49}$$



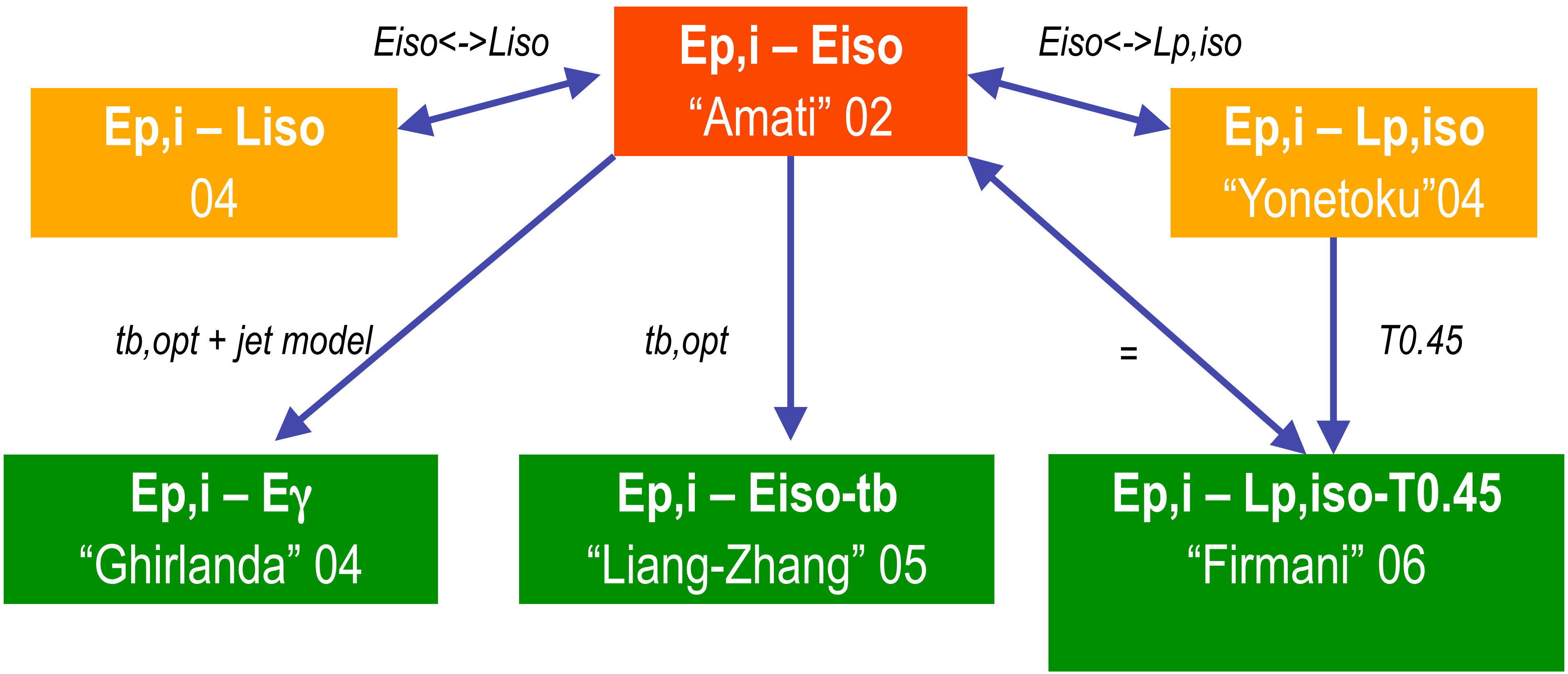


❑ … but Rossi et al. 2008 and Schaefer et al. 2008 , based on BeppoSAX and Swift GRBs, showed that the dispersion of the Lp-Ep-$T_{0.45}$ correlation is significantly higher than thought before and that the Ep,i-Lp,iso-T0.45 correlation my be equivalent to the Ep,i-Eiso correlation





❑ Ep – “intensity” (or “spectrum-energy”) correlations



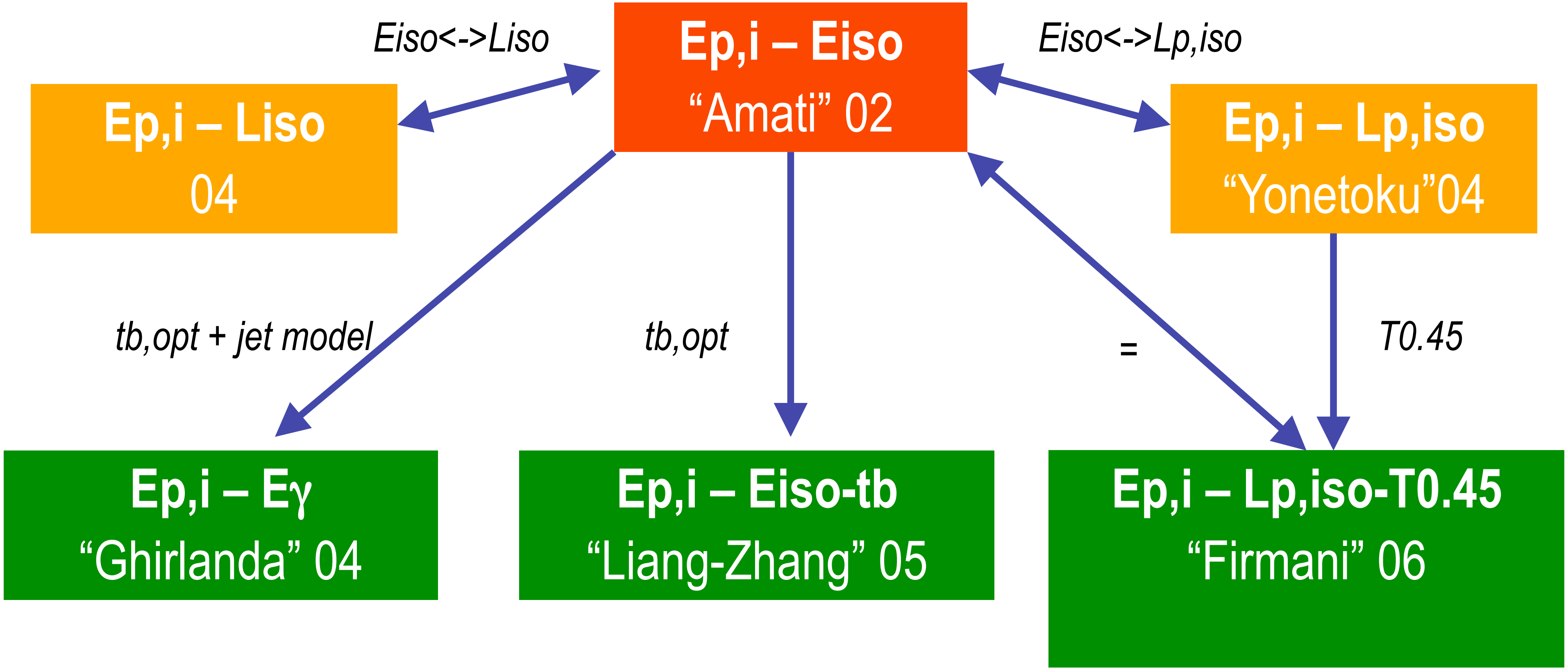
- **Eiso is the GRB brightness indicator with less systematic uncertainties**

- 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_{γ} ~ 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**

❑ Amati et al. (2008): let's make a step backward and **focus on the Ep,i – Eiso correlation**



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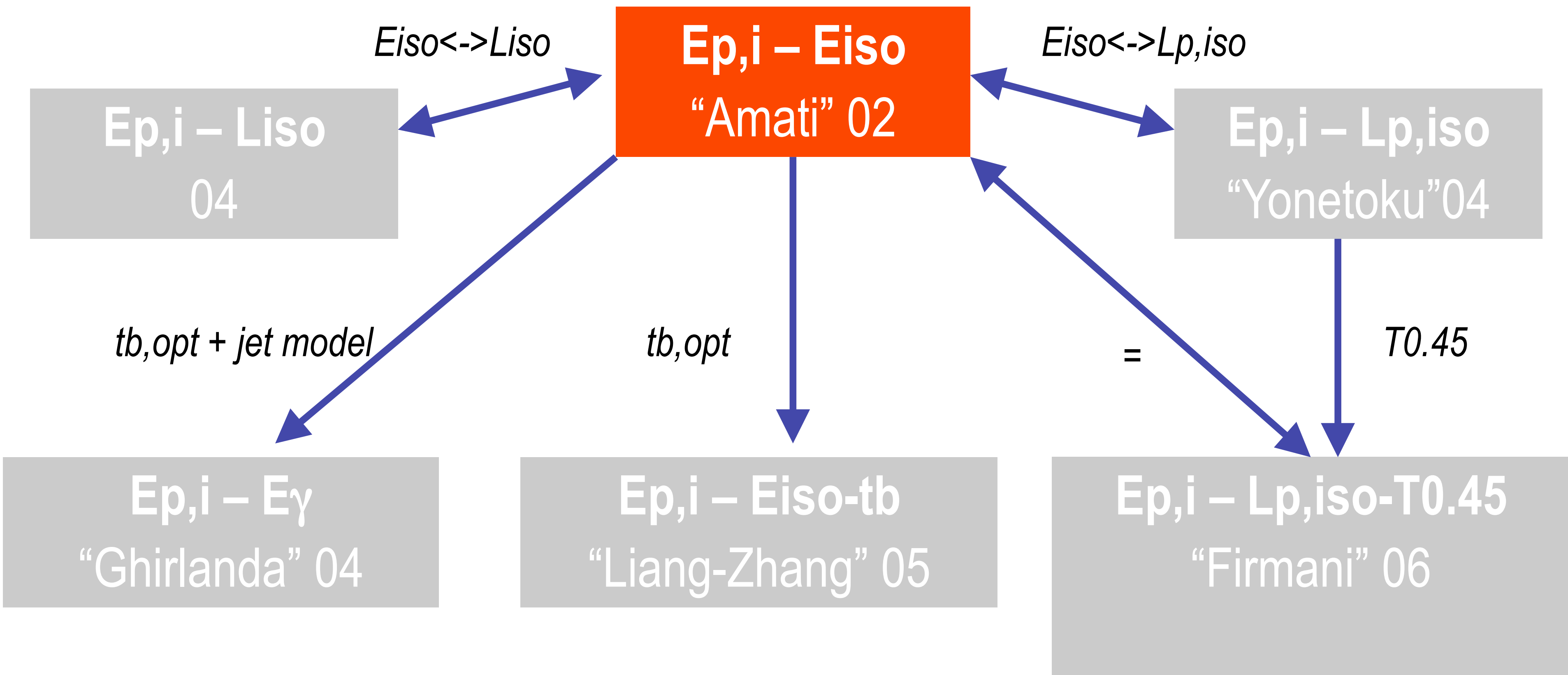
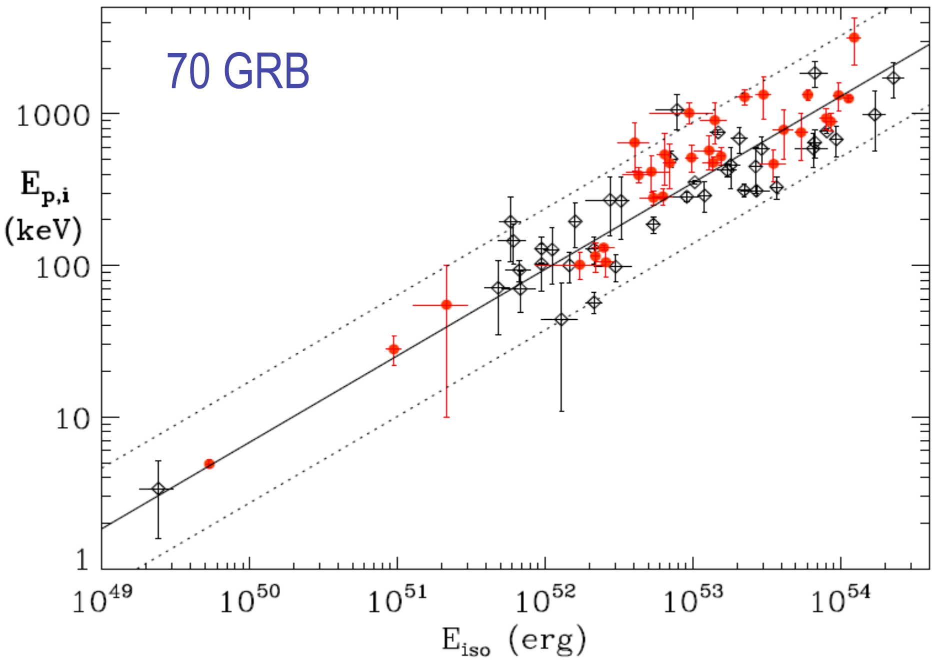
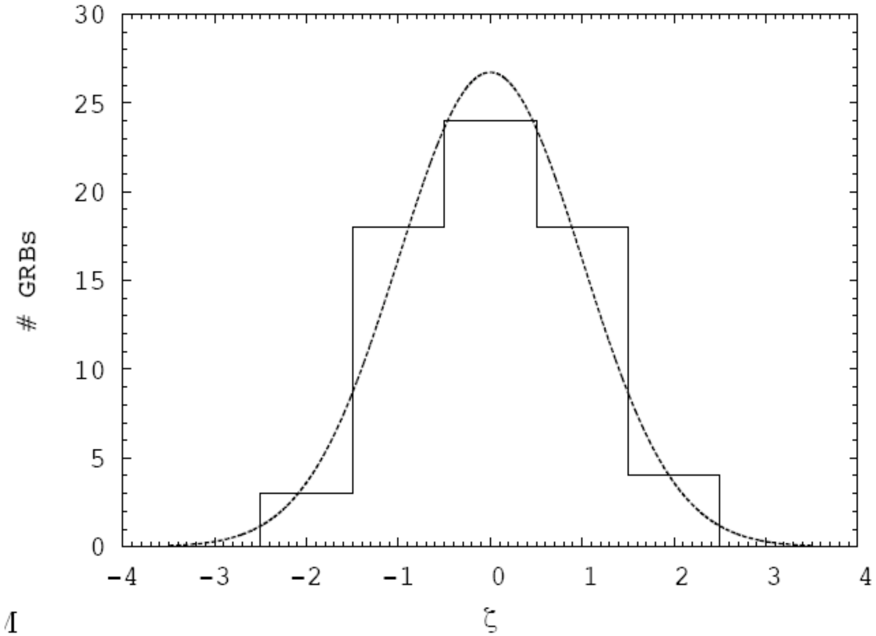


- **does the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation vary with the cosmological parameters used to compute E_{iso} ?**

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

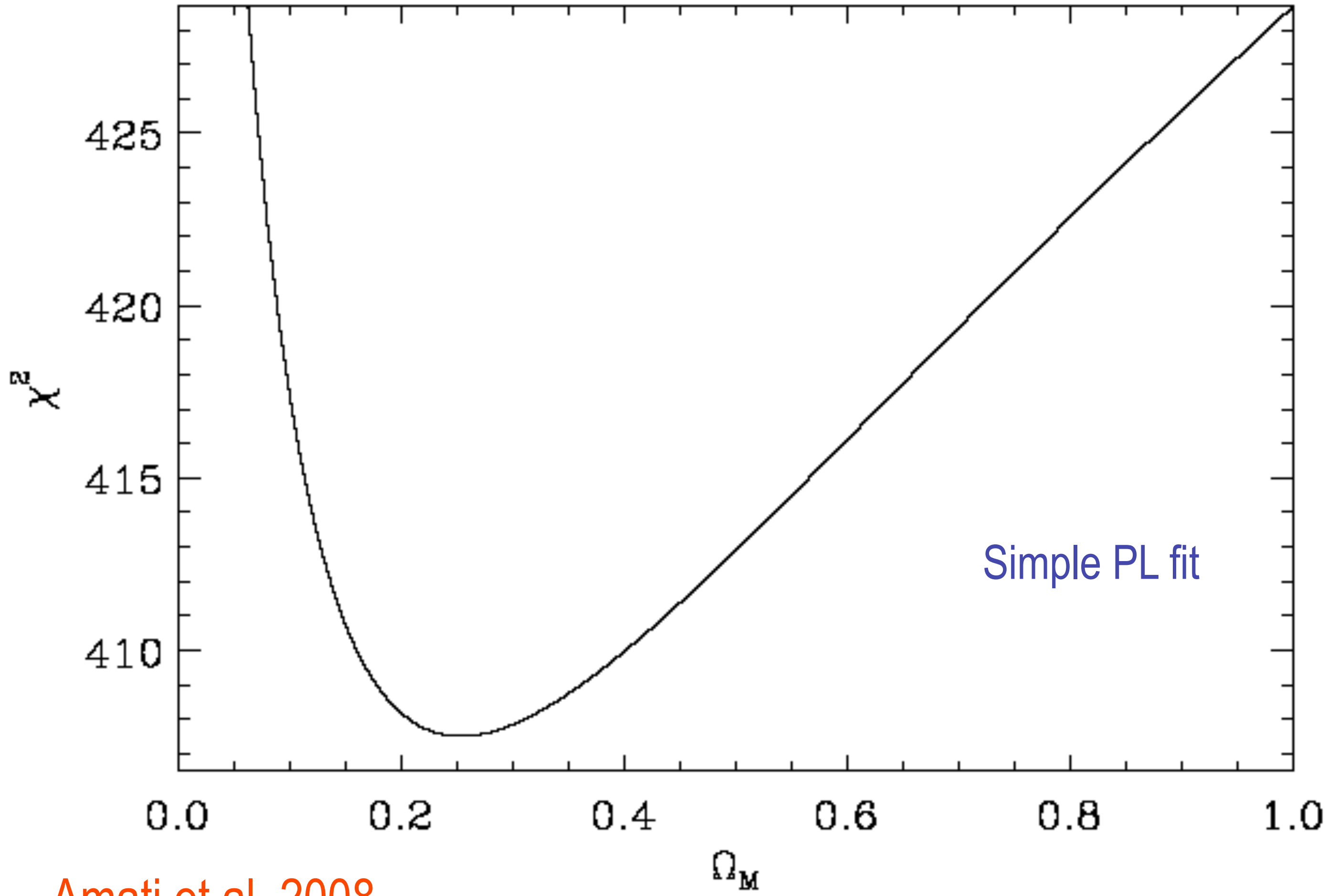
$$D_l = D_l(z, H_0, \Omega_M, \Omega_\Lambda, \ldots)$$





Amati et al. 2008

- 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



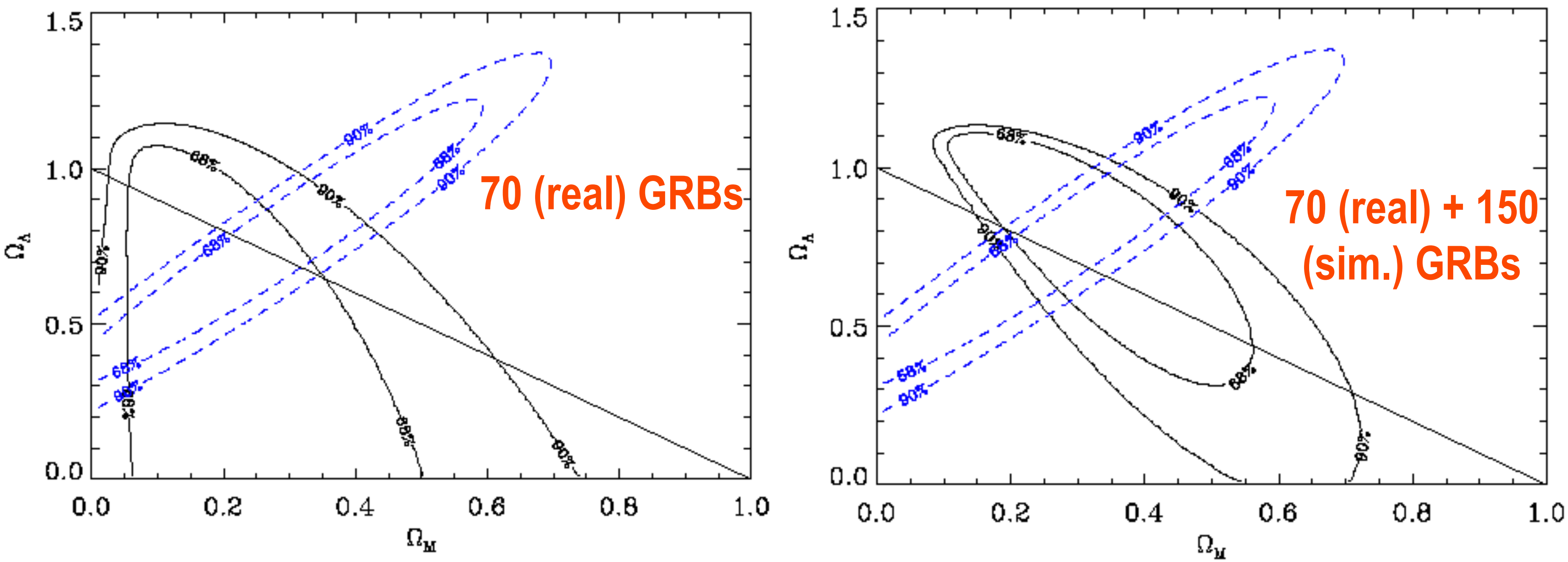
Amati et al. 2008

- By using a maximum likelihood method the extrinsic scatter can be parametrized and quantified (e.g., Reichart 2001, D'Agostini 2005)

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

- Ω_M can be constrained 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.)

- significant constraints on both Ω_M and Ω_Λ expected from sample enrichment

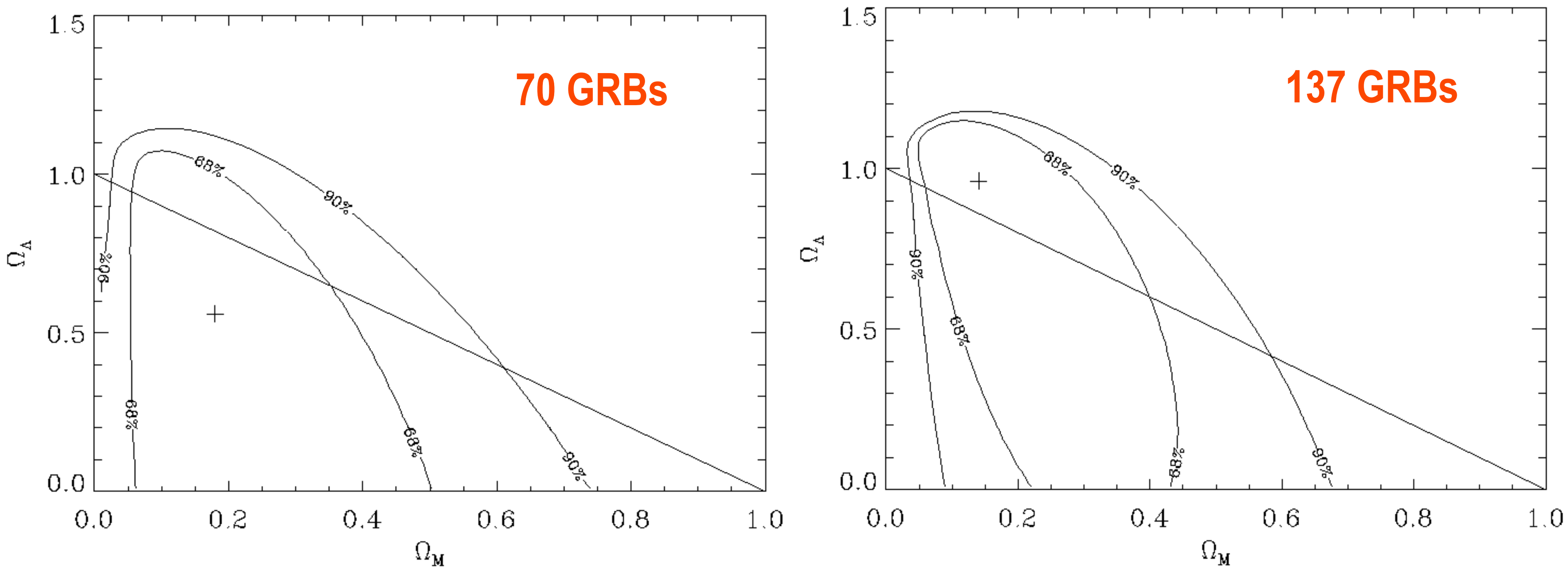


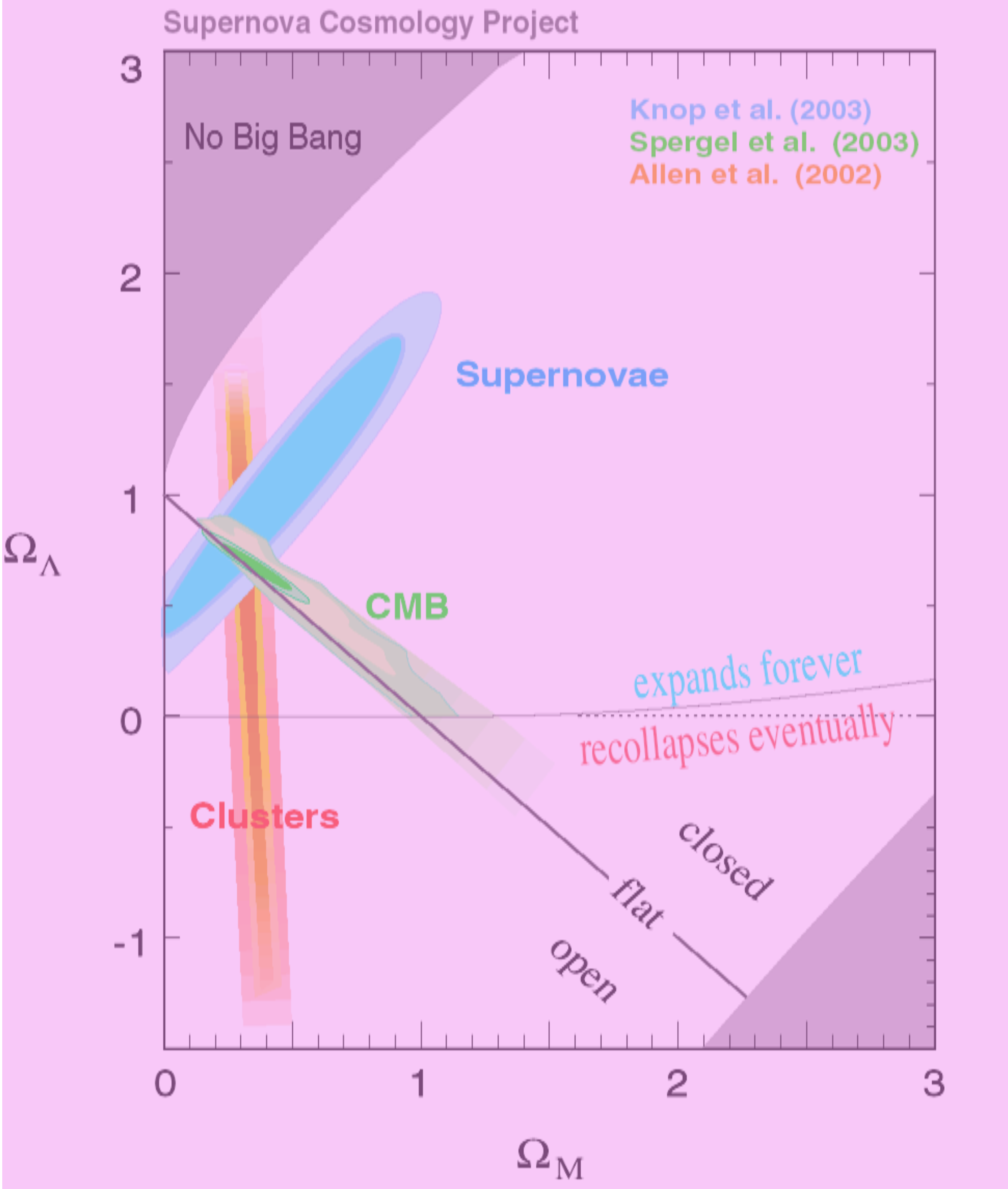
Amati et al. 2008

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

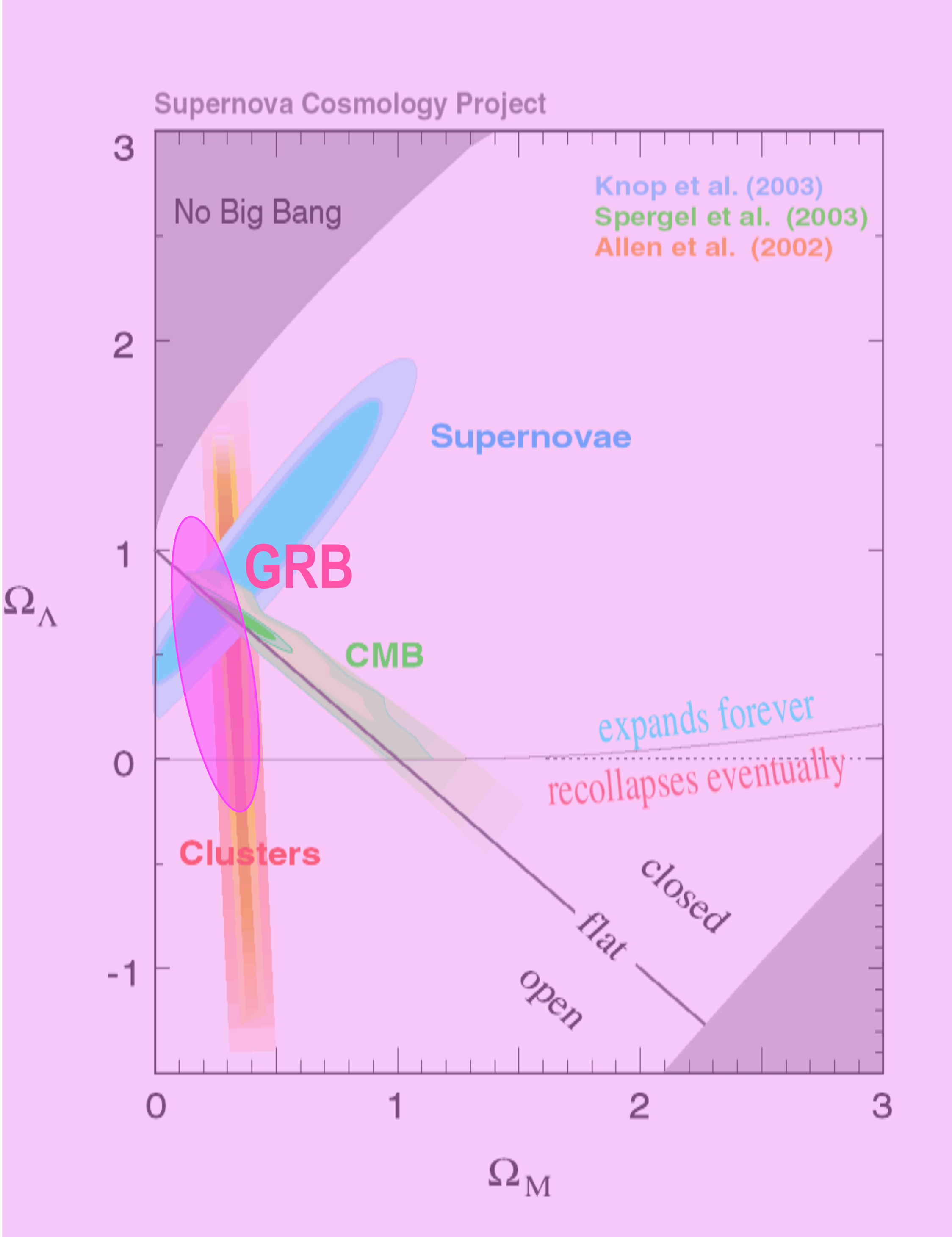
➢ this evidence supports the reliability and perspectives of the use of the Ep,i – Eiso correlation for the estimate of cosmological parameters

Ωm (flat universe)	68%	*90%*
70 GRBs (Amati+ 08)	0.04 – 0.43	0.02 – 0.71
137 GRBs (Amati+ 12)	0.06 – 0.34	0.03 – 0.54





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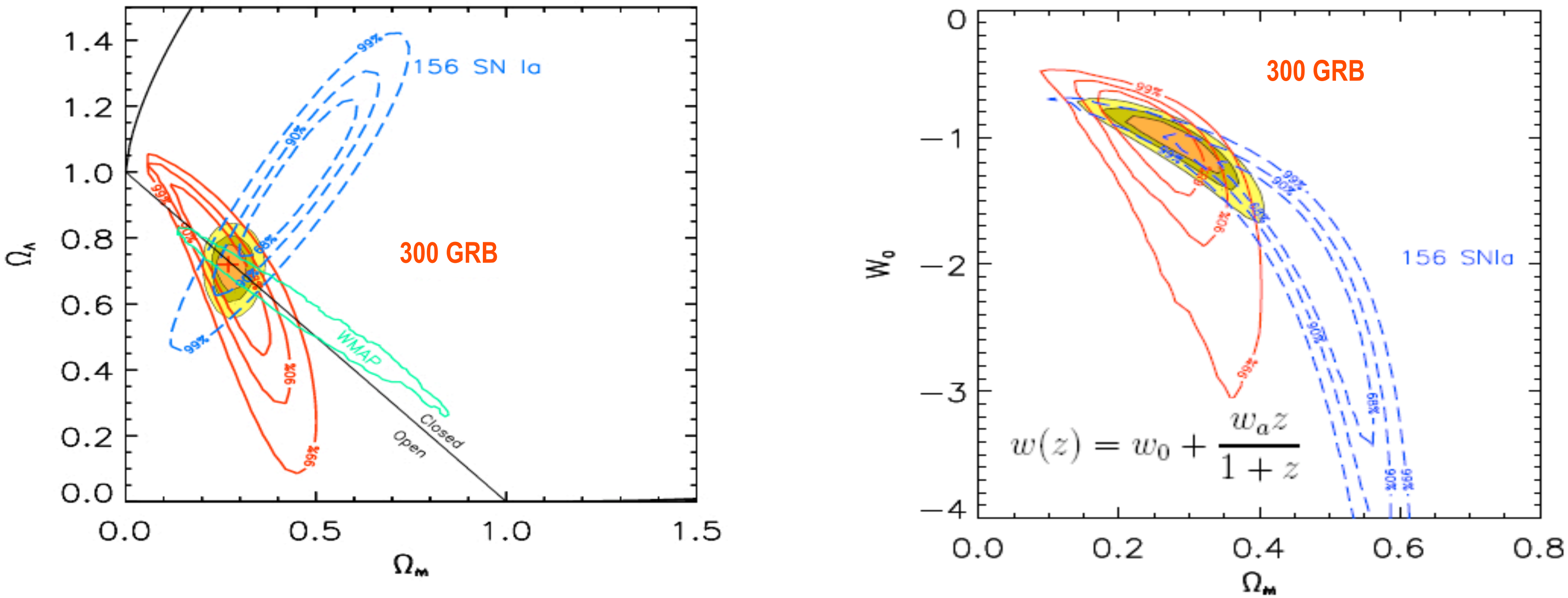
Perspectives

- 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 15-20 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)



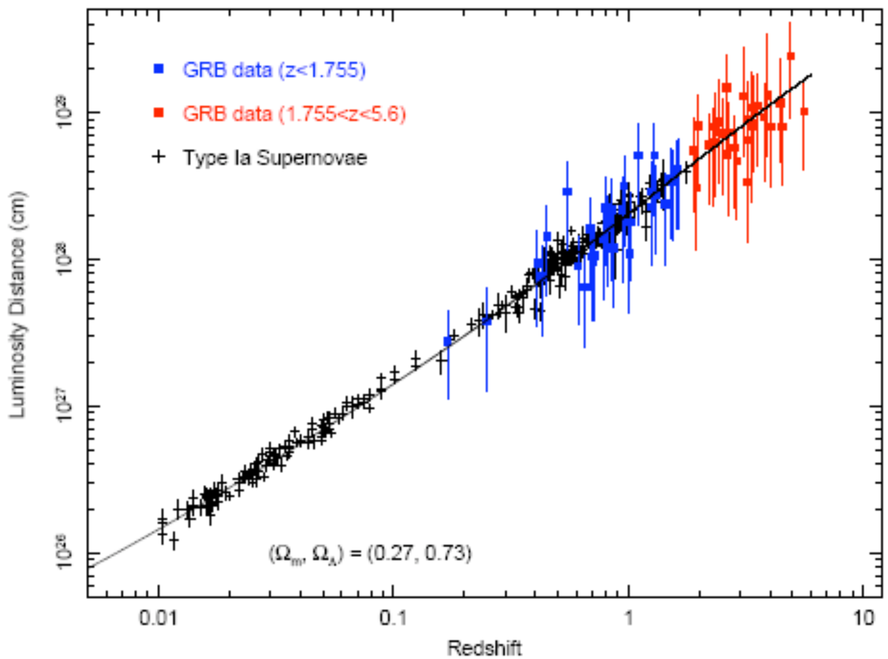
Adapted from Amati+ 12 and Ghirlanda+ 2007

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

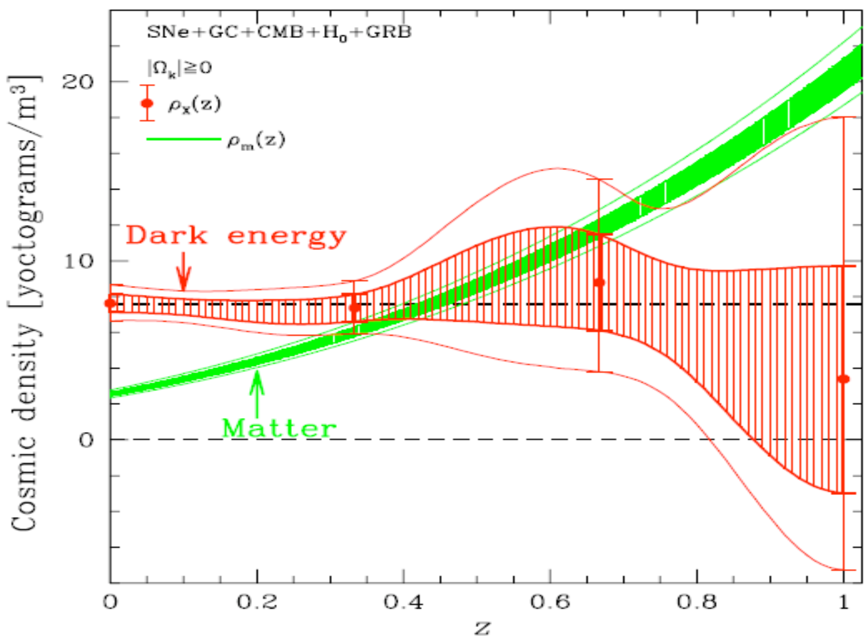
- Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at z < 1.7 by using the luminosity distance – redshift relation derived for SN Ia

- The aim is to extend the SN Ia Hubble diagram up to redshift where the luminosity distance is more sensitive to dark energy properties and evolution

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



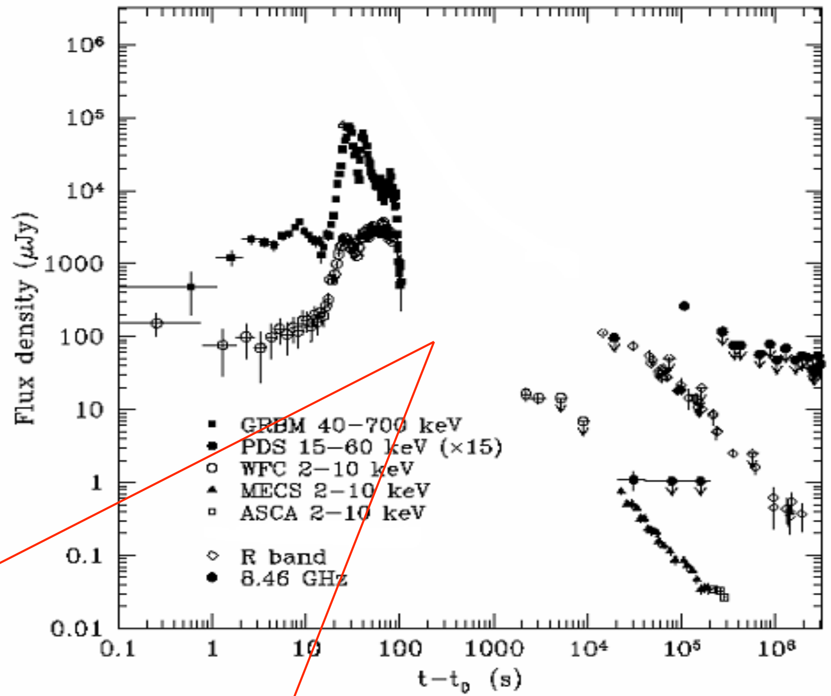
Kodama et al. 2008

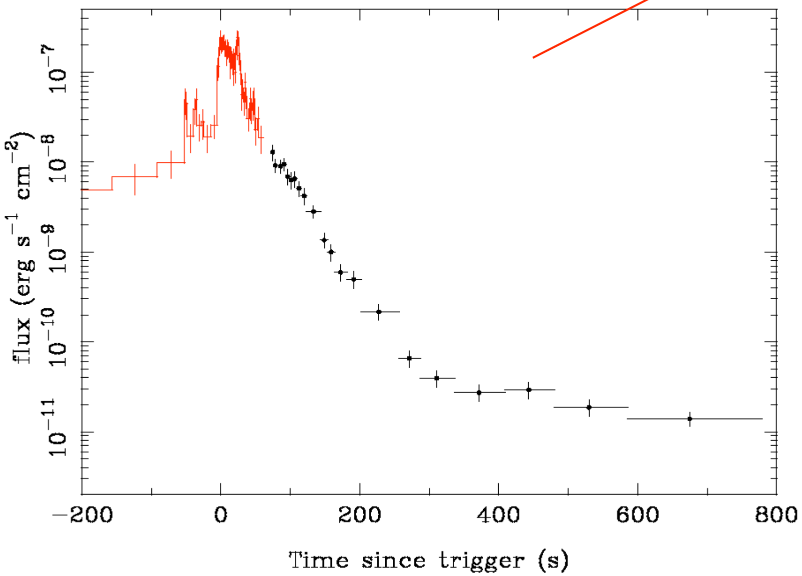


Wang et al. 2012

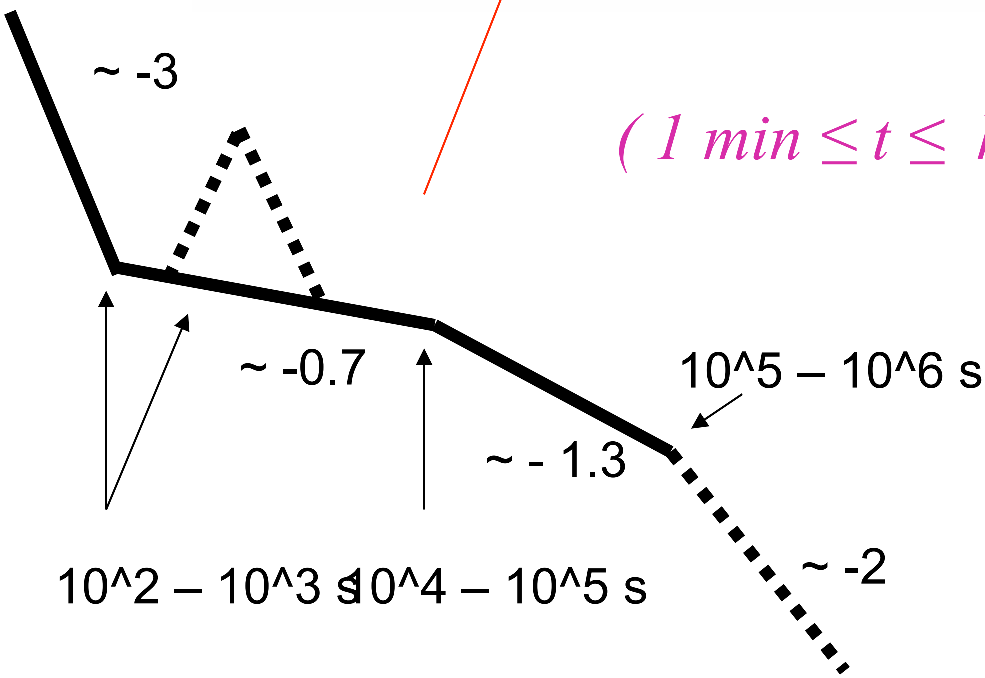
❑ Investigating correlations involving afterglow properties

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





Swift team

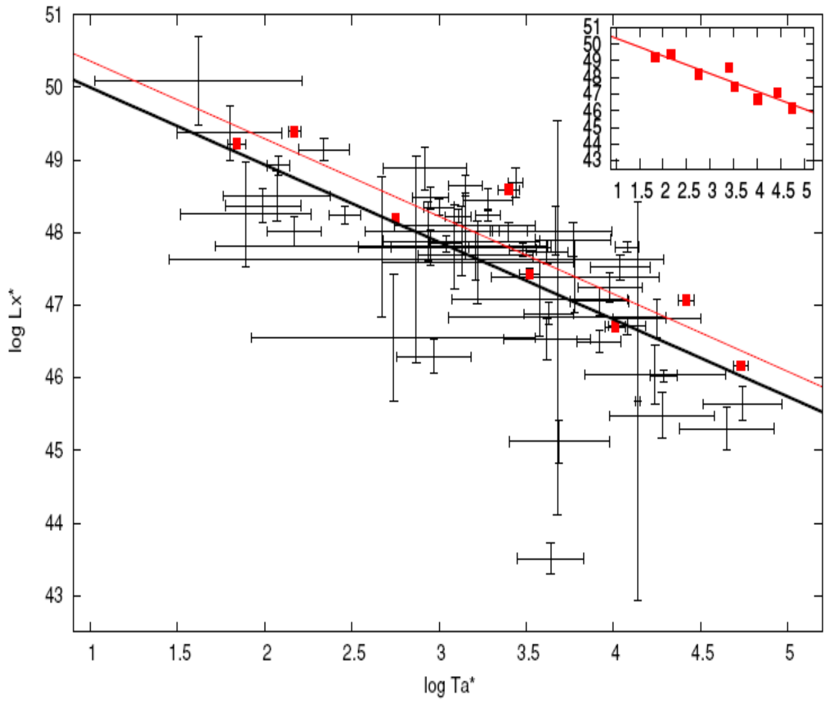


(1 min ≤ t ≤ hours)

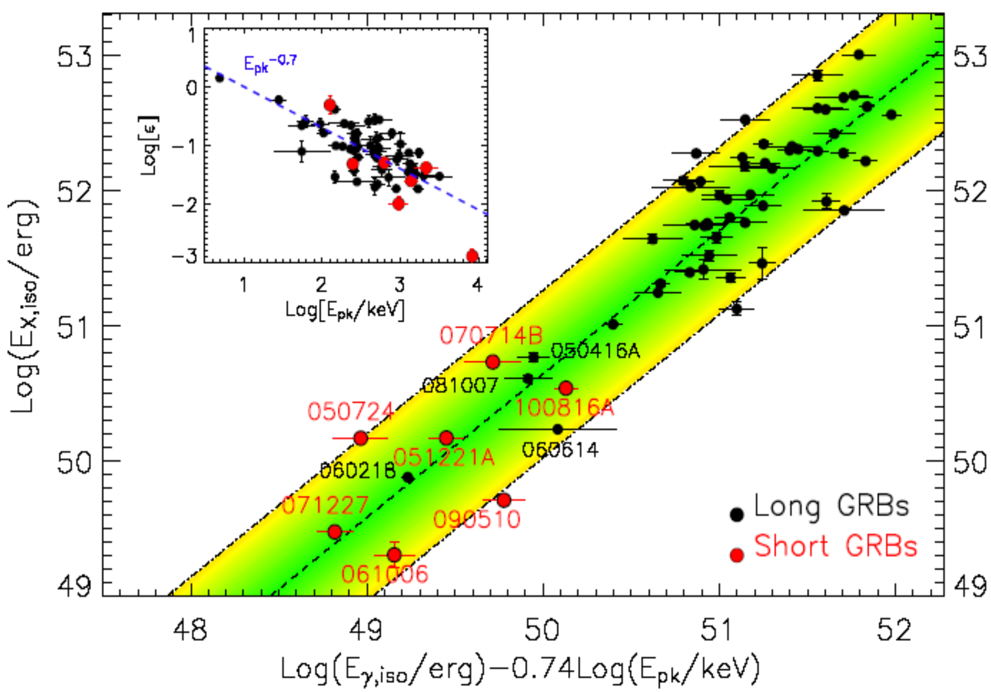
➢ A correlation between the time, Ta, and the luminosity, Lx, of the end of the "plateau phase" in GRB X-ray afterglows is being investigated (Dainotti+ 2008,2010)

➢ A three-parameters correlation between Ep,i, Eiso and Ex,iso has been recently reported (Margutti et al. 2012, Bernardini et al. 2012)

➢ If confirmed and refined by further analysis, these correlations may be complementary to the Ep,i – intensity correlation for standardizing GRBs



Dainotti et al. 2012

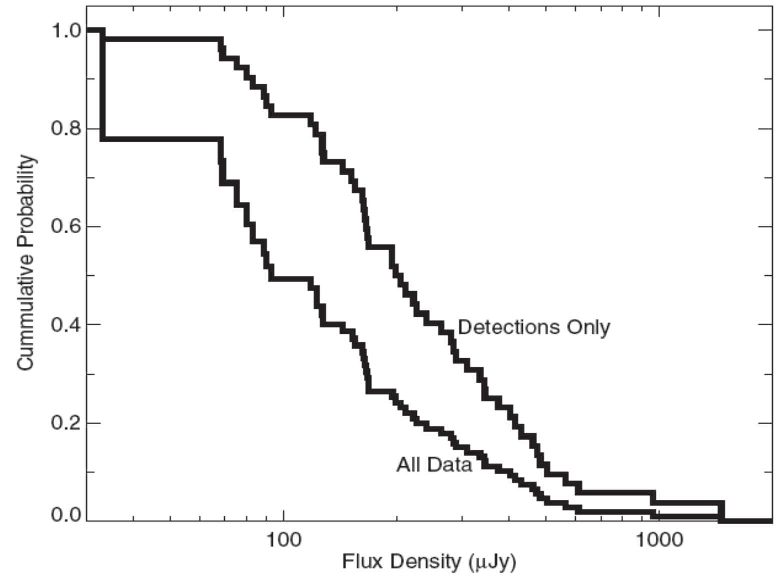


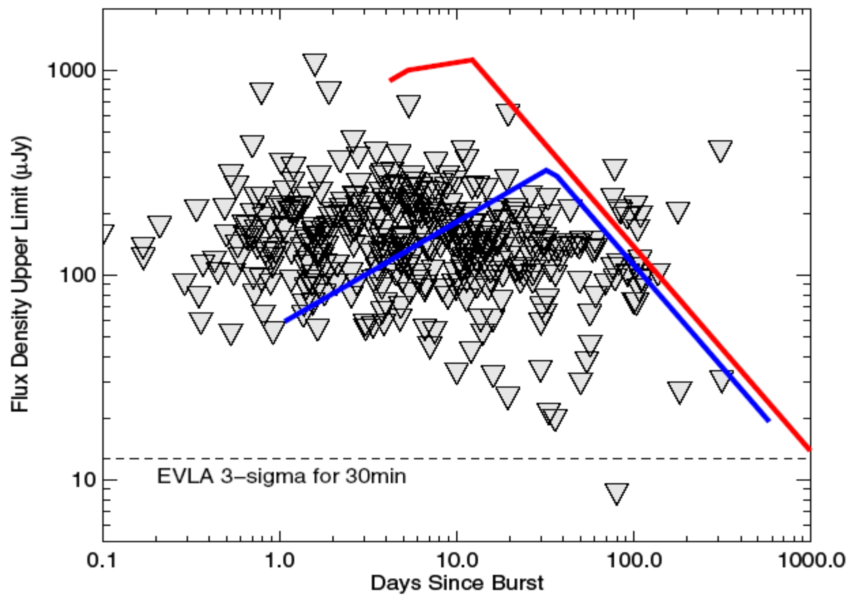
Margutti et al. 2012

The SKA contribution

❑ Radio properties of GRBs

- In the "Swift era", radio afterglow emission is being detected for about 30% accurately (< a few arcmin) localized GRBs (~93% in X-rays, ~75% in optical/ NIR)
- Most detections by VLA / EVLA (Frail et al, Chandra et al.); several detections also by WSRT, ATCA, GMRT; a few by VLBA.
- The canonical long-duration GRB radio light curve at 8.5 GHz peaks at three to six days in the source rest frame, with a median peak luminosity of 10^{31} erg s^{-1} Hz^{-1}.
- The typical mean fluxes at 8.5 GHz in 5 -10 days from the GRB range from ~100 to ~900 μJy. Peak fluxes may reach 10 mJy

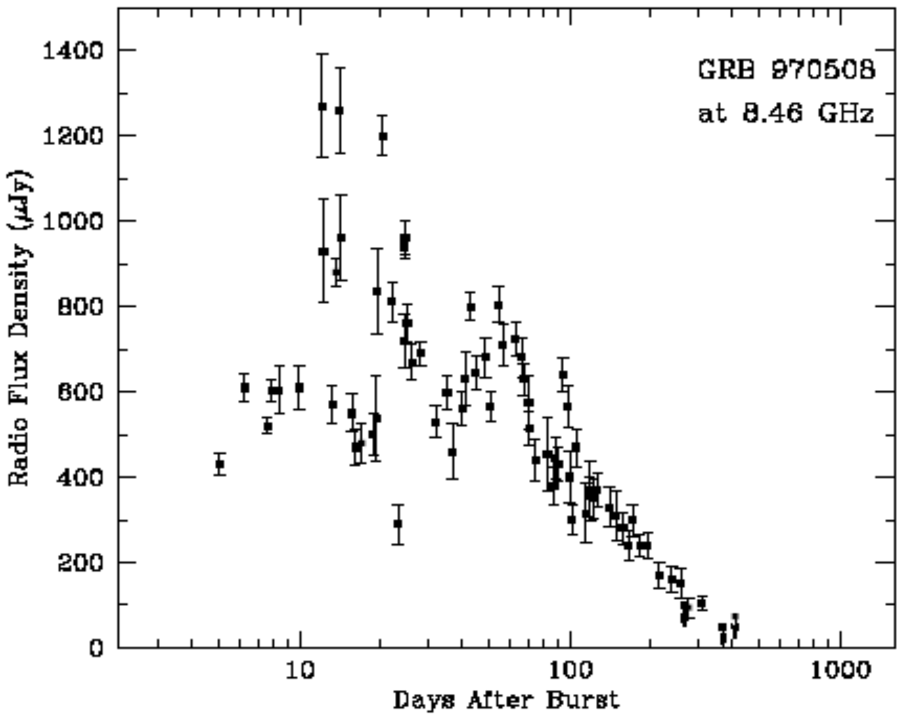


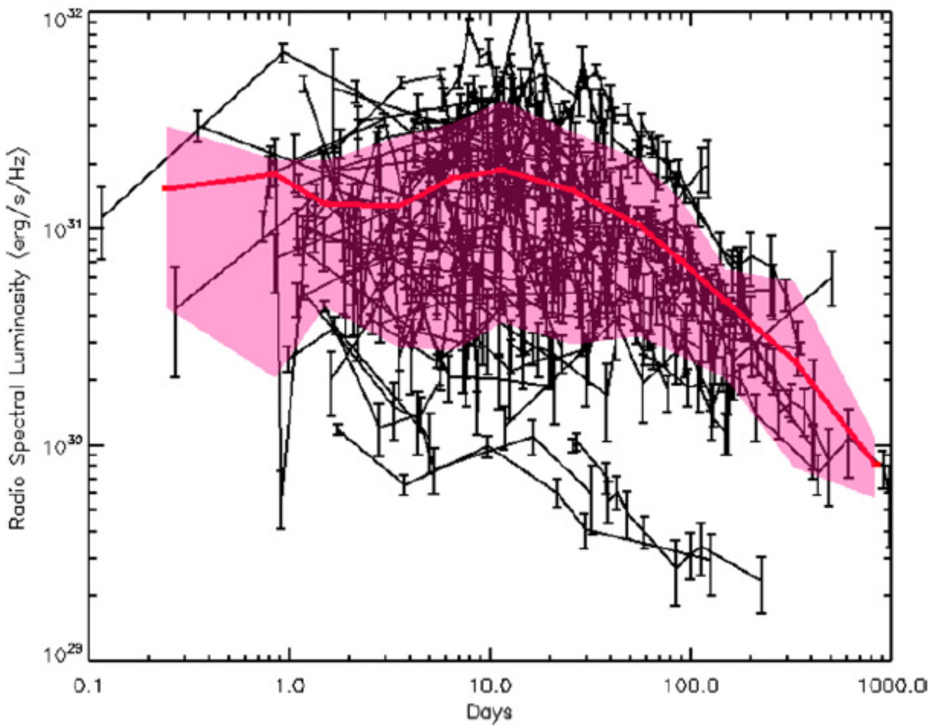


Chandra & Frail 2012

❑ Relevance of radio observations of GRBs

- ➢ Scintillation: fundamental probe of ultra-relativistic expansion of GRB sources
- ➢ Test of afterglow models unbiased, w/r, e.g., to optical observations (dust extinction, contamination by SN and host galaxy light





Frail et al. 1997:

Chandra & Frail 2012

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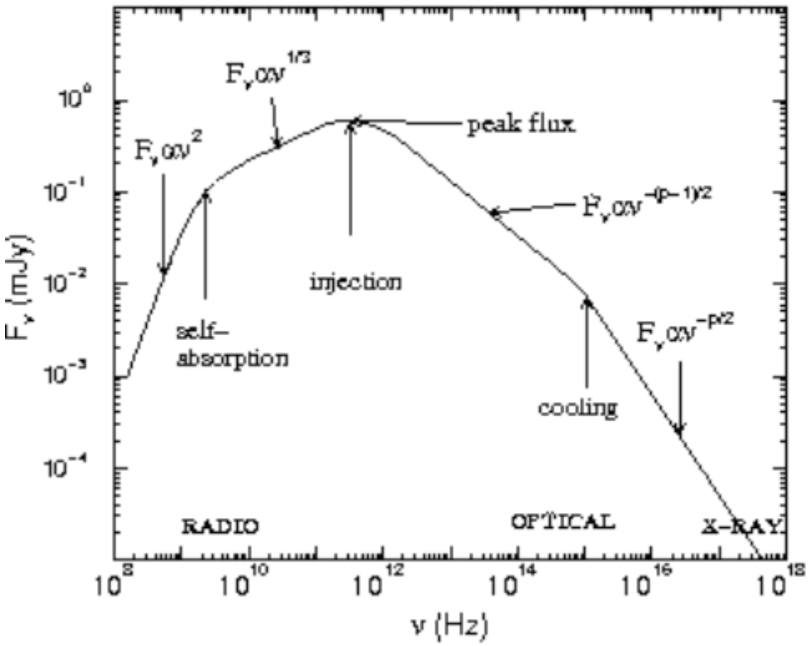
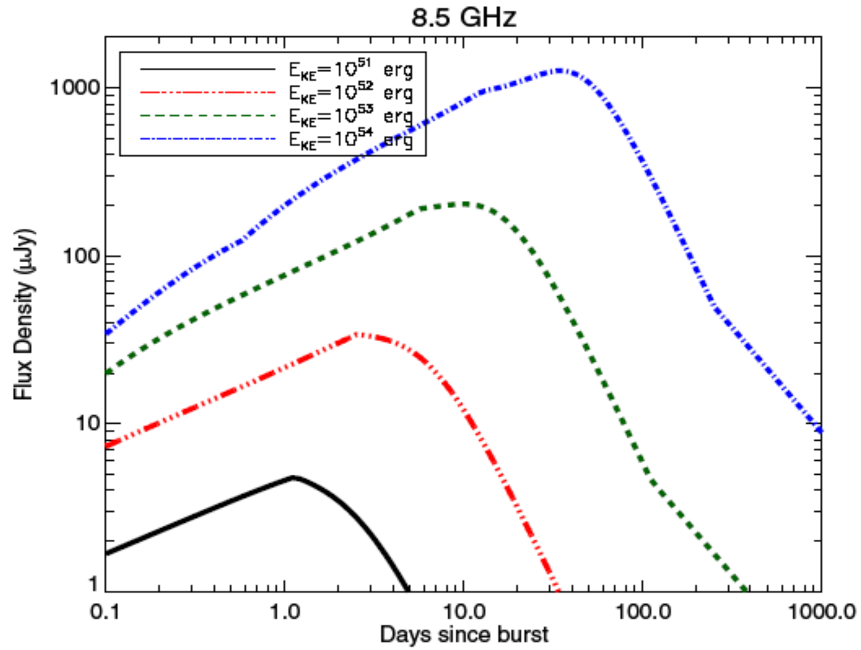
- Properties of circum-burst environment
- Late time non relativistic phase expansion (LC and SED): afterglow physics and determination of the blast-wave energy independent of the initial jet collimation
- Statistics of orphan afterglows: inference on maximum jet opening angle





Measure: F_m, ν_m, ν_c, ν_a, t_{jet} ➔ Infer: E_k, $n(r)$, ε_e, ε_B, θ_{jet}

Chandra & Frail 2012

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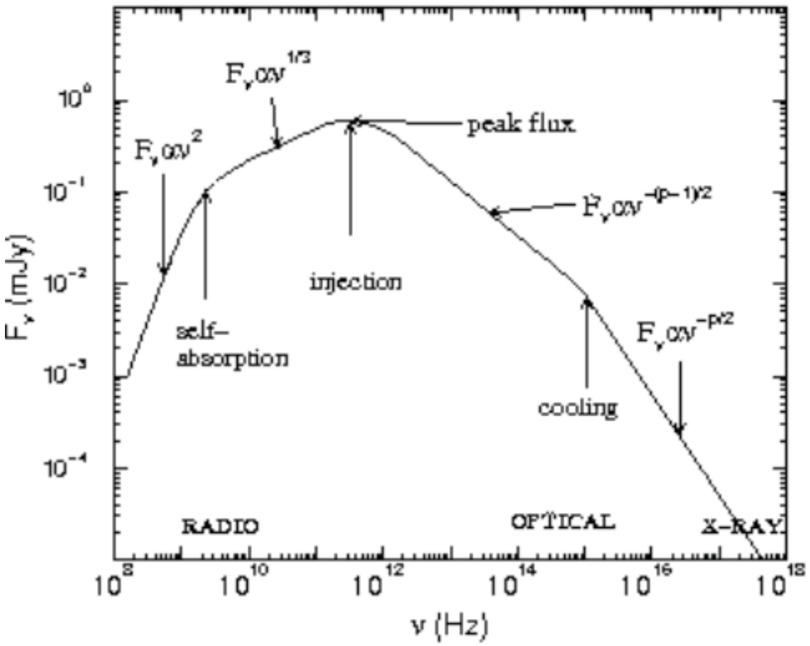

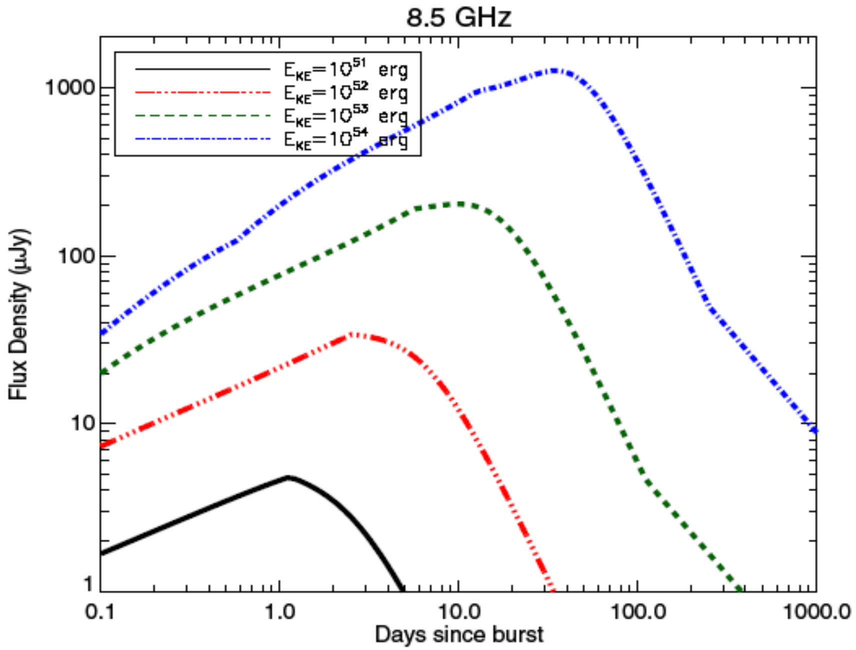

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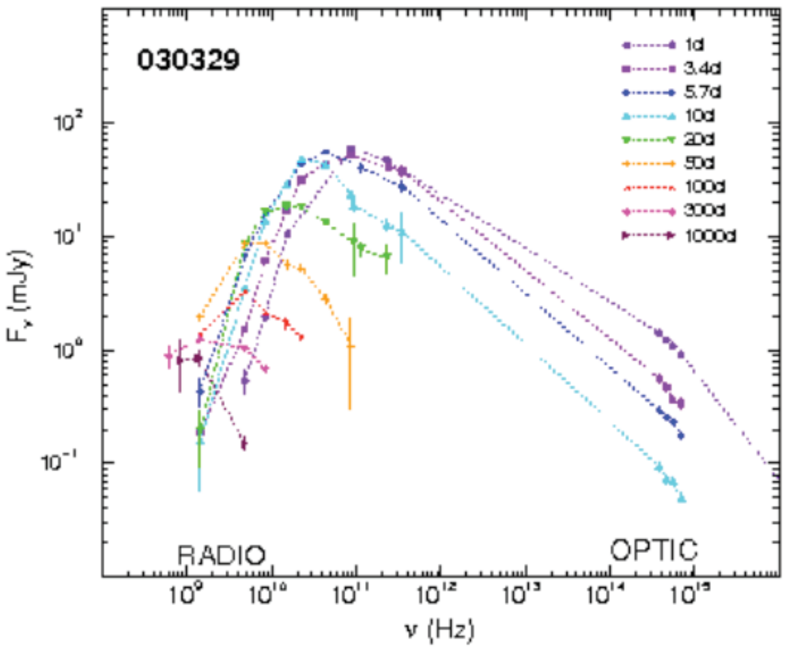
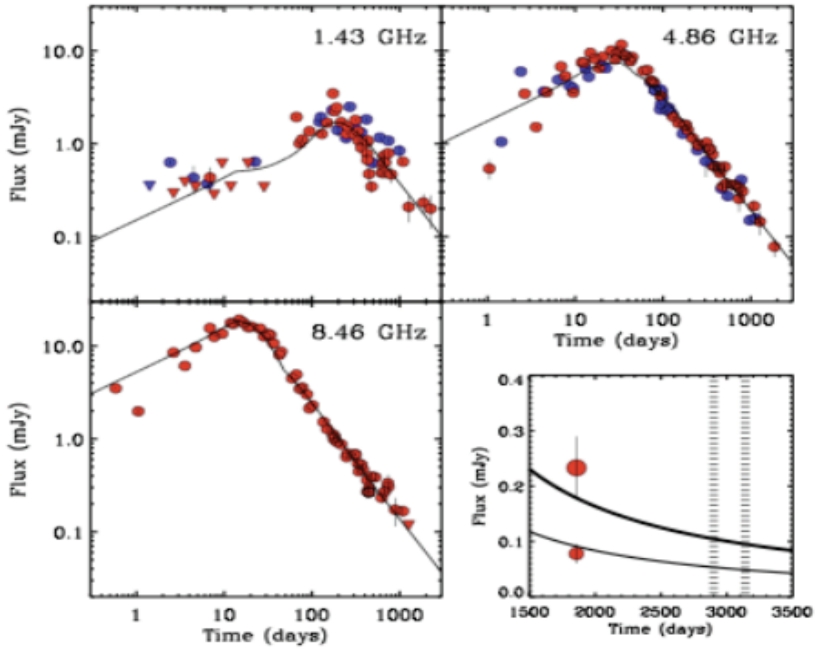


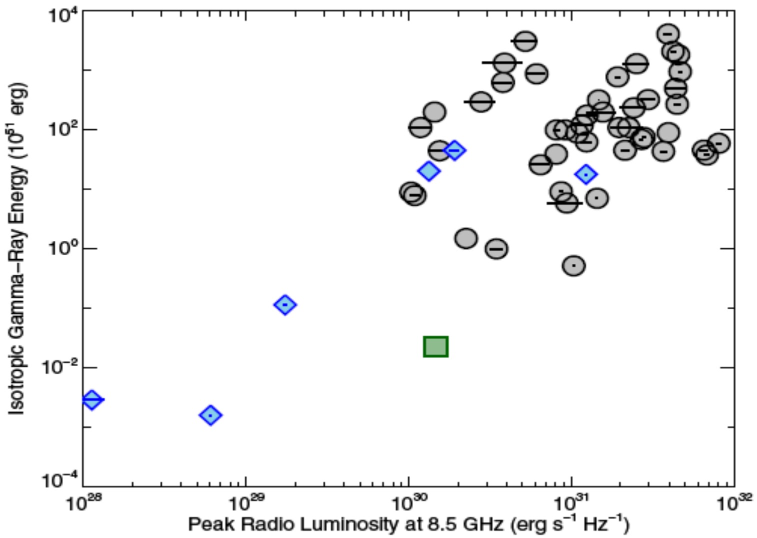


Measure: F_m, ν_m, ν_c, ν_a, t_{jet} ➔ Infer: E_k, $n(r)$, ε_e, ε_B, θ_{jet}

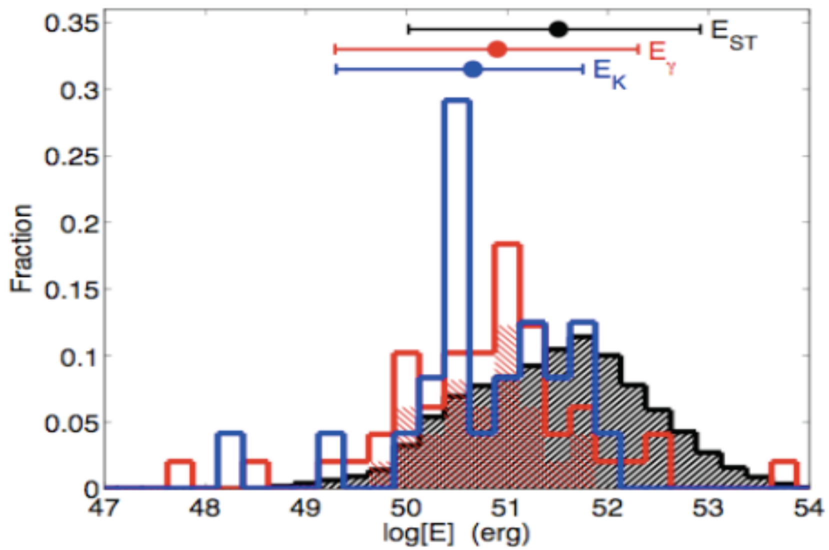
Soderberg et al. 2011

❑ SKA for GRBs

- High sensitivity + high angular resolution + short reaction time + broad band: measurement of GRB source size and expansion velocity through ISM scintillation; accurate location of GRBs in host galaxies; early radio afterglow: physics (reverse shock, transition from optically thick to optically thin synchrotron emission, …); kinetic energy and jet opening angle from SED fitting; host galaxy radio emission
- High sensitivity: increased number and accuracy of GRBs radio calorimetry; detection of very high z GRBs (up to z 10 ?); study of SFR up to very high z; nearby (z <1) low-luminosity GRBs and GRB/SNe;
- Broad FOV: significant number of orphan afterglows -> constraints on distribution of GRB jet opening angles and, hence, of energy budget



Chandra & Frail 2012



Shivers & Berger 2011

❑ SKA for cosmology with GRBs

- High sensitivity + high angular resolution + short reaction time + broad band: measurement of GRB source size and expansion velocity through ISM scintillation; accurate location of GRBs in host galaxies; early radio afterglow: **physics** (reverse shock, transition from optically thick to optically thin synchrotron emission, …); **kinetic energy and jet opening angle** from SED (X, opt. , IR, radio) fitting;
- High sensitivity: **increased number and accuracy of GRBs radio calorimetry**; **detection of very high z GRBs (up to z 10 ?);** study of SFR up to very high z; nearby (z <1) low-luminosity GRBs and GRB/SNe;
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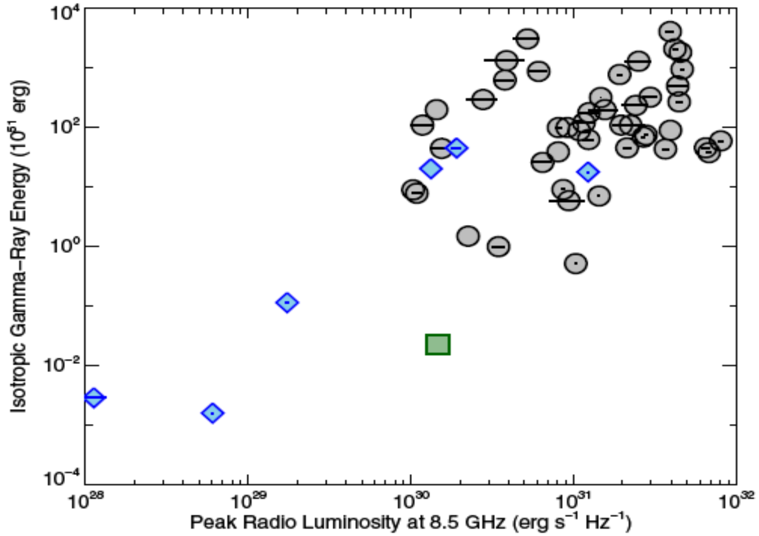
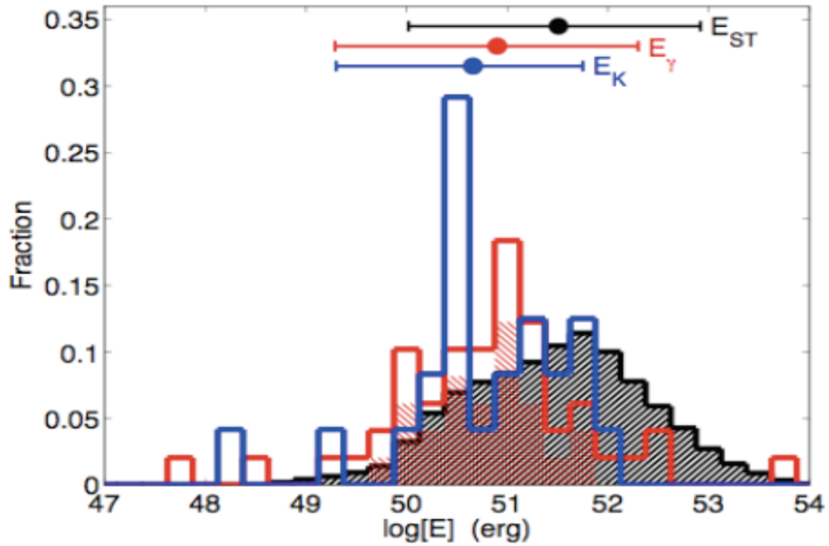


Chandra & Frail 2012



Shivers & Berger 2011

Conclusions and perspectives

- 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 – Eiso 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 ~ 0.25, 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 (e.g., SVOM) and more investigations (physics, methods, calibration) will allow to go beyond SN Ia cosm. (e.g.,dark energy EOS)
- **Radio observations by SKA will give a significant contribution by providing unique clues to the physics, energy budget and beaming angle of GRBs**