The $E_{p,i} - E_{iso}$ «Amati» relation

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

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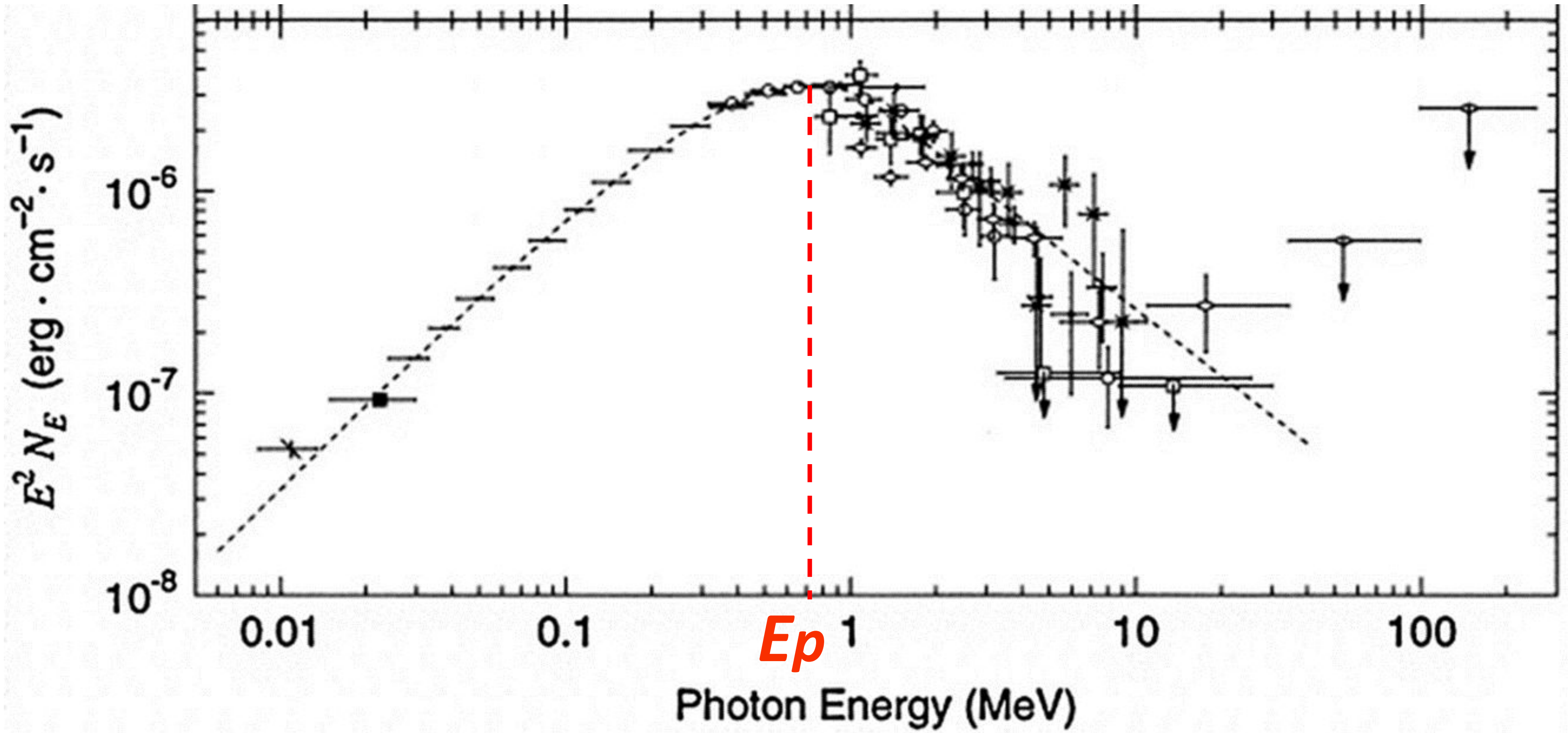
OAS

V Congresso Nazionale GRB
12-15 settembre 2022

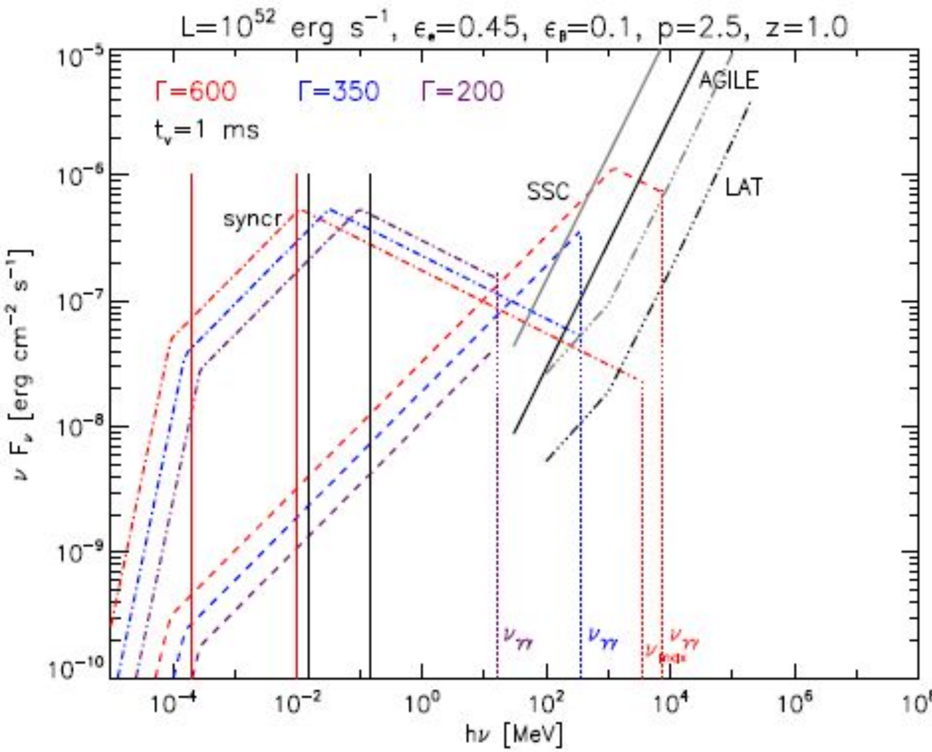
Ep,i and Eiso

- GRB $\nu F\nu$ spectra typically show a peak at a characteristic photon energy E_p

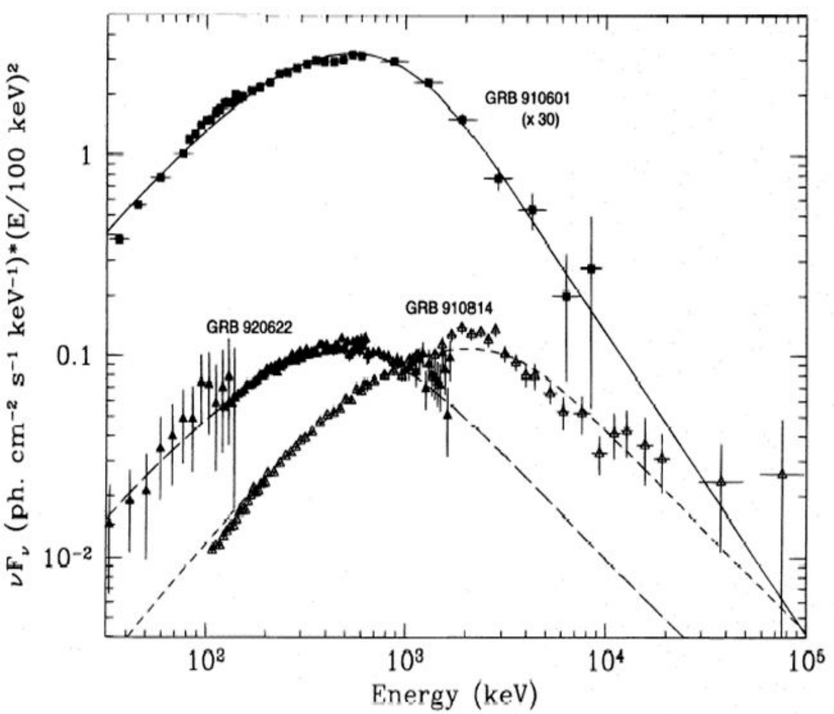


Ep,i and Eiso

 e.g., in synchrotron shock models (SSM) **Ep** corresponds to a characteristic frequency (possibly ν_m in fast cooling regime) or to the temperature of the Maxwellian distribution of the emitting electrons



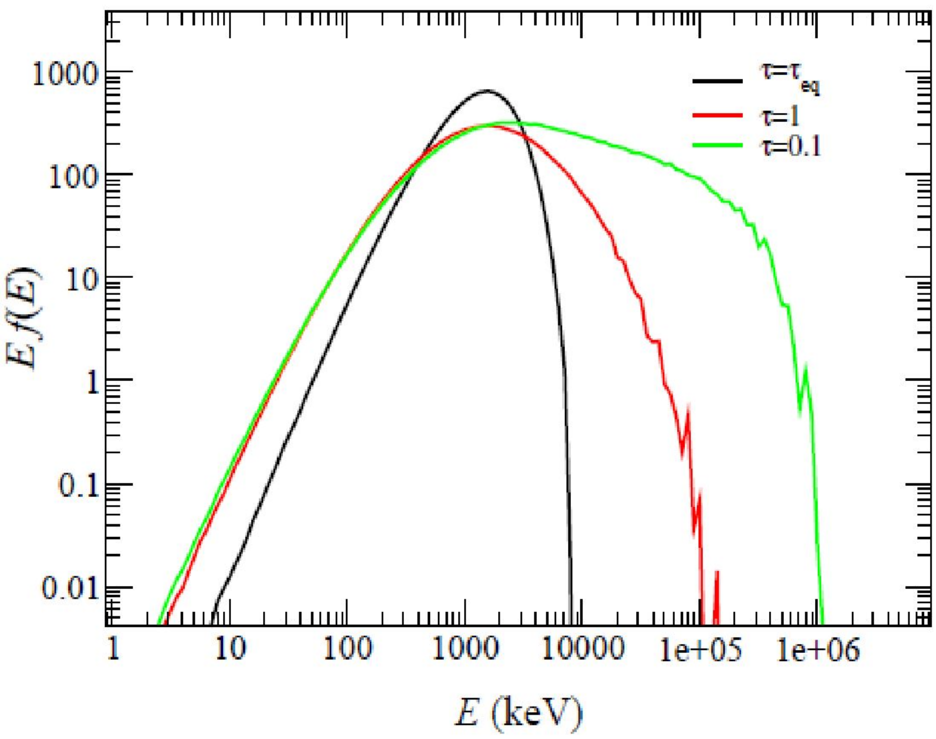
Galli & Guetta 2007



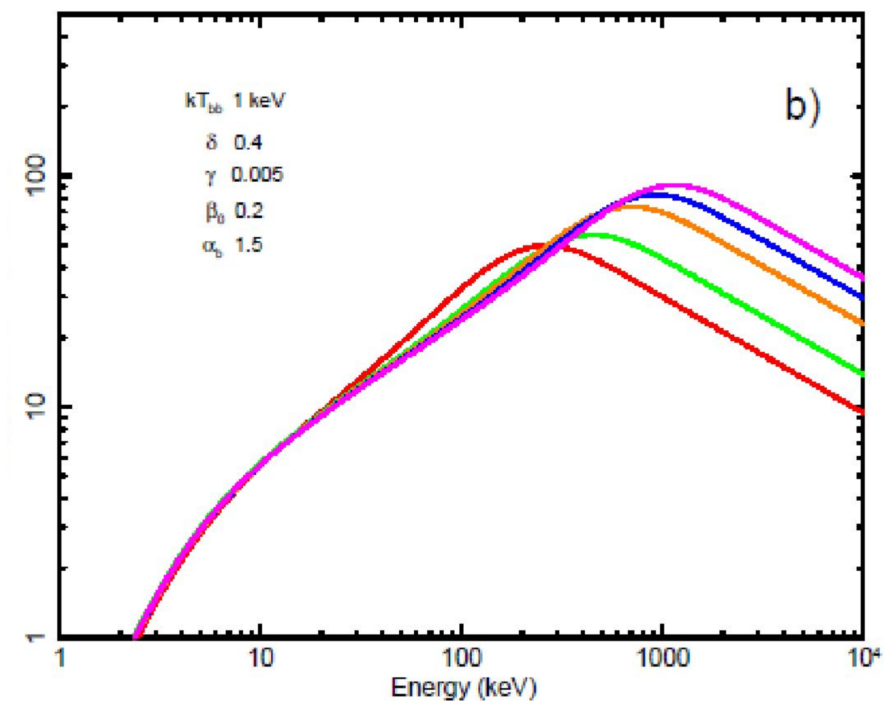
Tavani, ApJ, 1995

Ep,i and Eiso

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



Giannios 2012



Titarchuk et al., ApJ, 2012

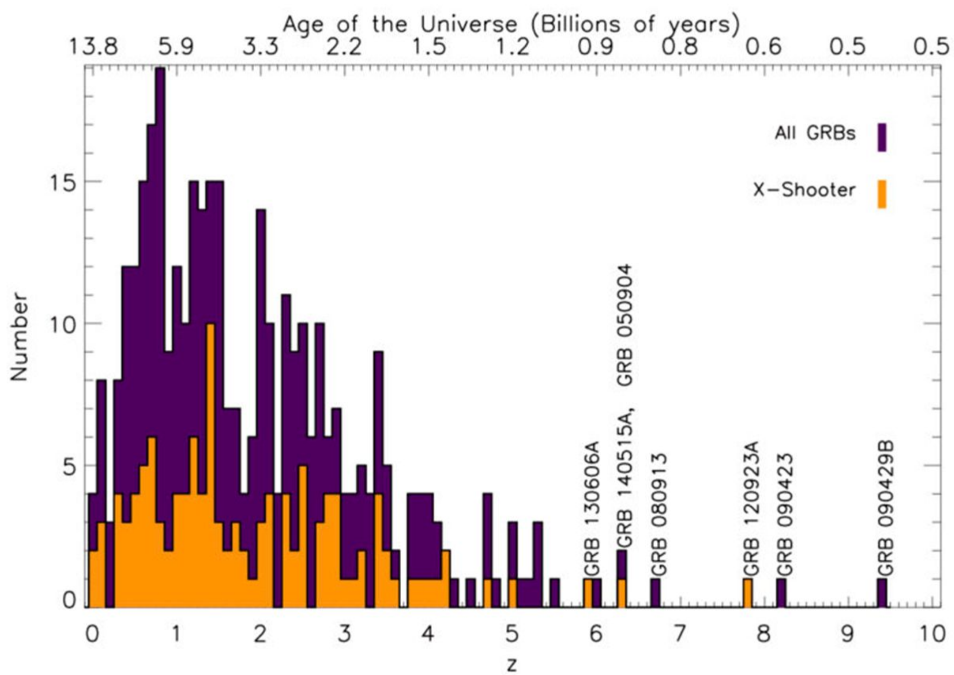
Ep,i and Eiso

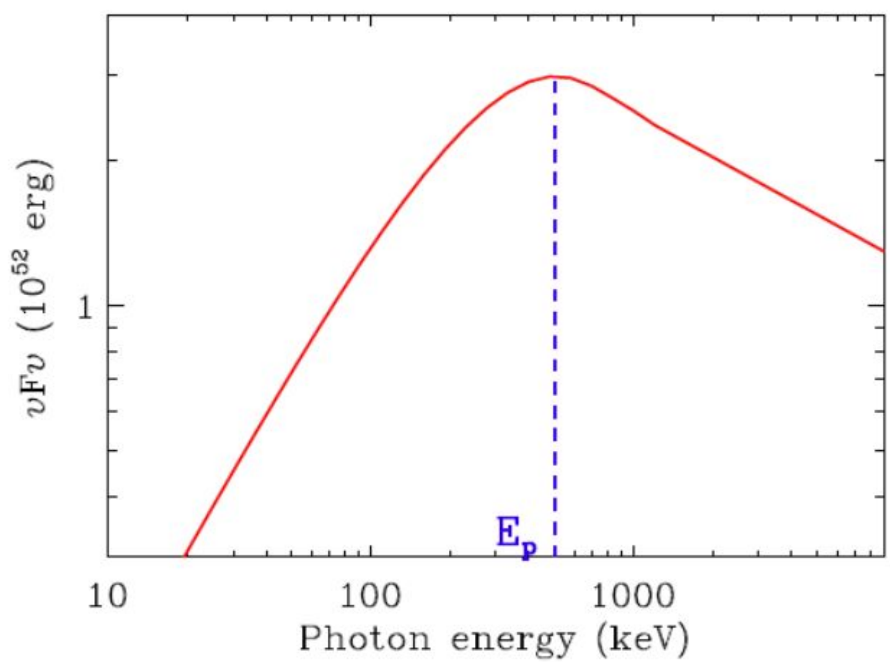
measured time-integrated spectrum + measured redshift

-> intrinsic peak energy $E_{p,i}$ and radiated energy E_{iso}

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

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



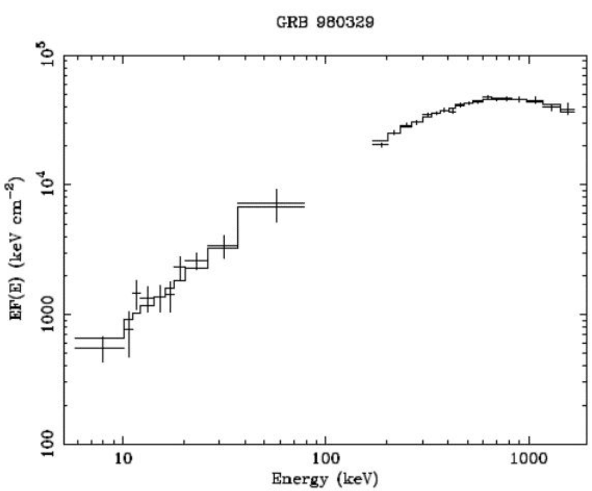


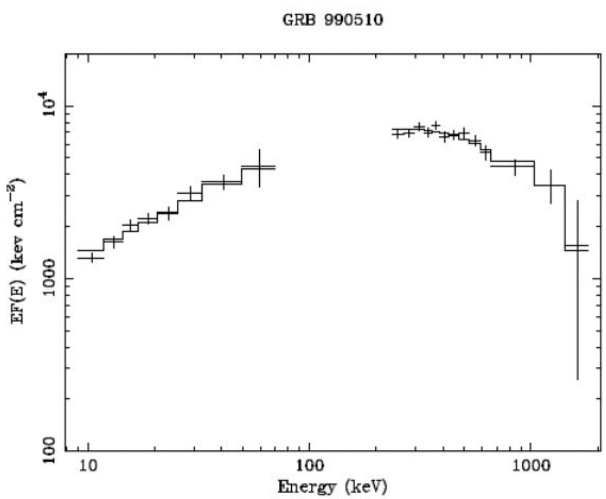
Discovery: Amati et al., A&A, 2002

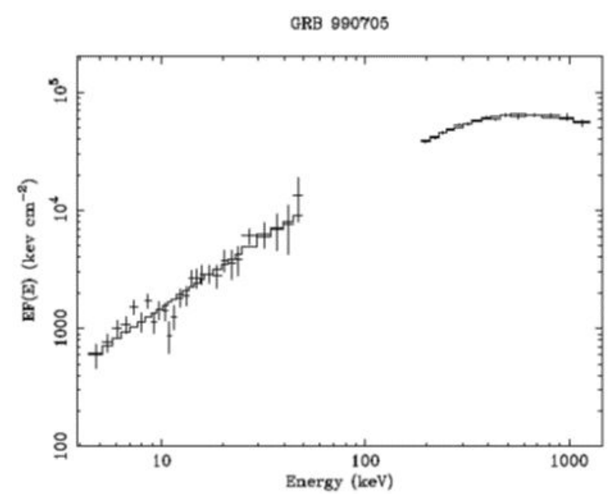
Intrinsic spectra and energetics of BeppoSAX Gamma–Ray Bursts with known redshifts

L. Amati[1], F. Frontera[1,2], M. Tavani[3], J. J. M. in 't Zand[4], A. Antonelli[5], E. Costa[6], M. Feroci[6], C. Guidorzi[2], J. Heise[4], N. Masetti[1], E. Montanari[2], L. Nicastro[7], E. Palazzi[1], E. Pian[8], L. Piro[6], and P. Soffitta[6]

Abstract. We present the main results of a study of spectral and energetics properties of twelve gamma-ray bursts (GRBs) with redshift estimates. All GRBs in our sample were detected by BeppoSAX in a broad energy range (2–700 keV). From the redshift estimates and the good-quality BeppoSAX time–integrated spectra we deduce the main properties of GRBs in their cosmological rest frames. All spectra in our sample are satisfactorily represented by the Band model, with no significant soft X–ray excesses or spectral absorptions. We find a positive correlation between the estimated total (isotropic) energies in the

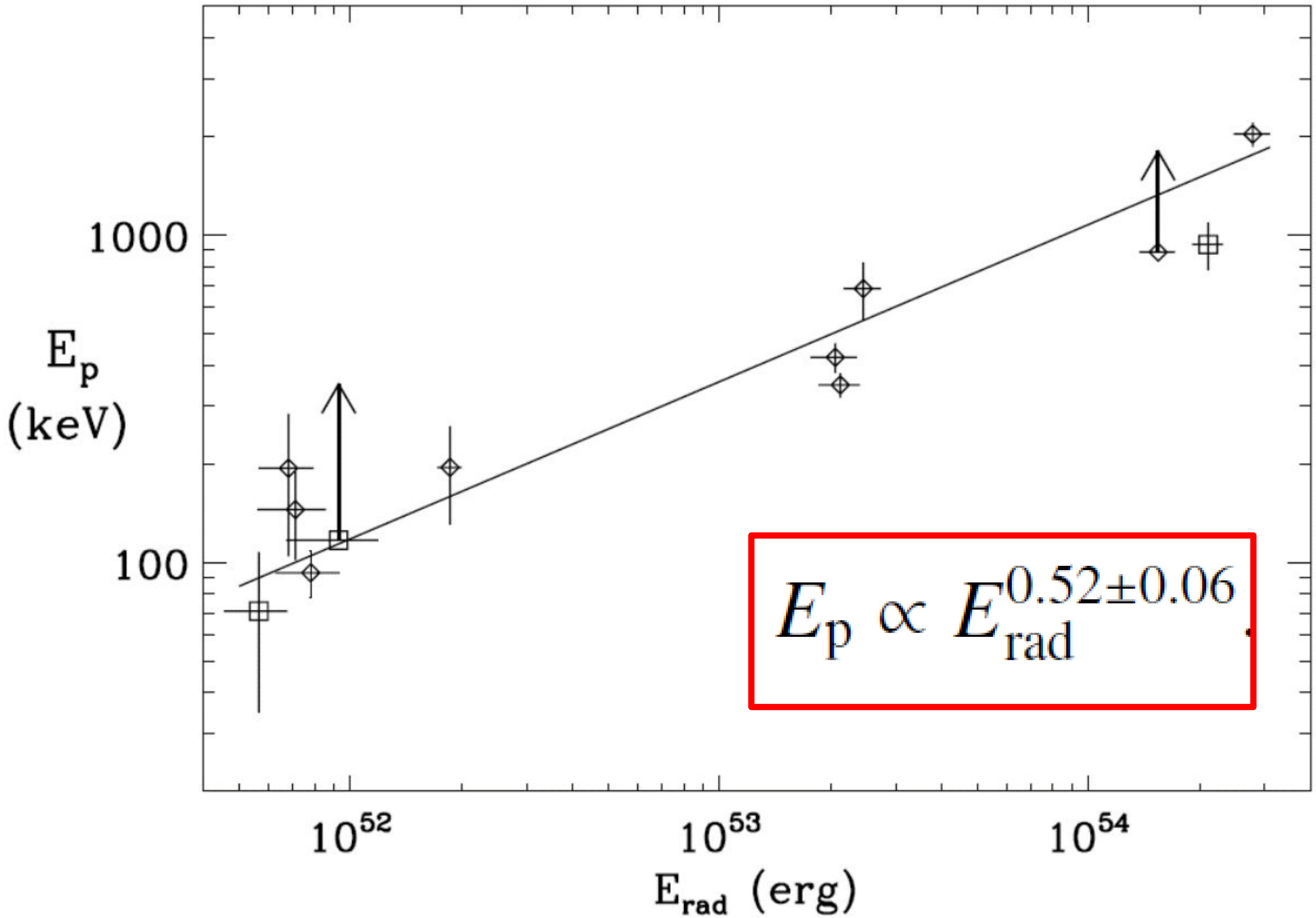






Discovery: Amati et al., A&A, 2002

Significant correlation between Ep,i and Eiso found based on first small sample of BeppoSAX GRBs with known redshift



The prophecy: Lloyd et al., ApJ, 2000

The possibility of a power-law correlation between Ep,i and Eiso was put forward based on large sample of BATSE spectra of GRBs without measured redshift

COSMOLOGICAL VERSUS INTRINSIC: THE CORRELATION BETWEEN INTENSITY AND THE PEAK OF THE νF_ν SPECTRUM OF GAMMA-RAY BURSTS

NICOLE M. LLOYD,[1] VAHÉ PETROSIAN,[1] AND ROBERT S. MALLOZZI[2]

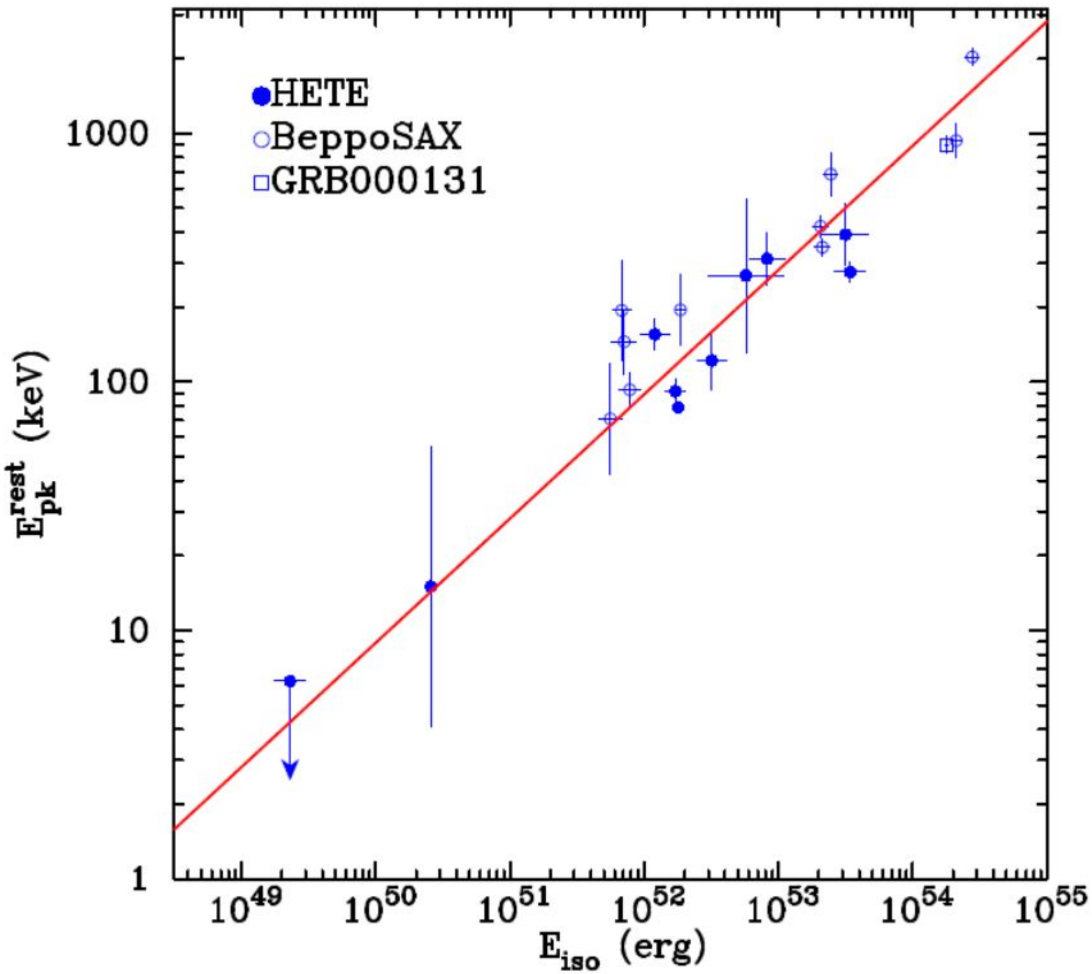
Received 1999 August 16; accepted 1999 December 10

We present results of correlation studies, examining the association between the peak of the νF_ν spectrum of gamma-ray bursts, E_p, with the burst's energy fluence and photon peak flux. We discuss methods of accounting for data truncation in E_p and fluence or flux when performing the correlation analyses. However, because bursts near the detector threshold are not usually able to provide reliable spectral parameters, we focus on results for the brightest bursts, in which we can better understand the selection effects relevant to E_p and burst strength. We find that there is a strong correlation between total fluence and E_p. We discuss these results in terms of both cosmological and intrinsic effects. In particular, we show that for realistic distributions of the burst parameters, cosmological expansion alone cannot account for the correlation between E_p and total fluence: the observed correlation is likely the result of an intrinsic relation between the burst rest-frame peak energy and the total radiated energy. We

The proclamation: D.Q. Lamb 2003

Ep,i - Eiso correlation confirmed and exteded to XRFs by HETE-2:

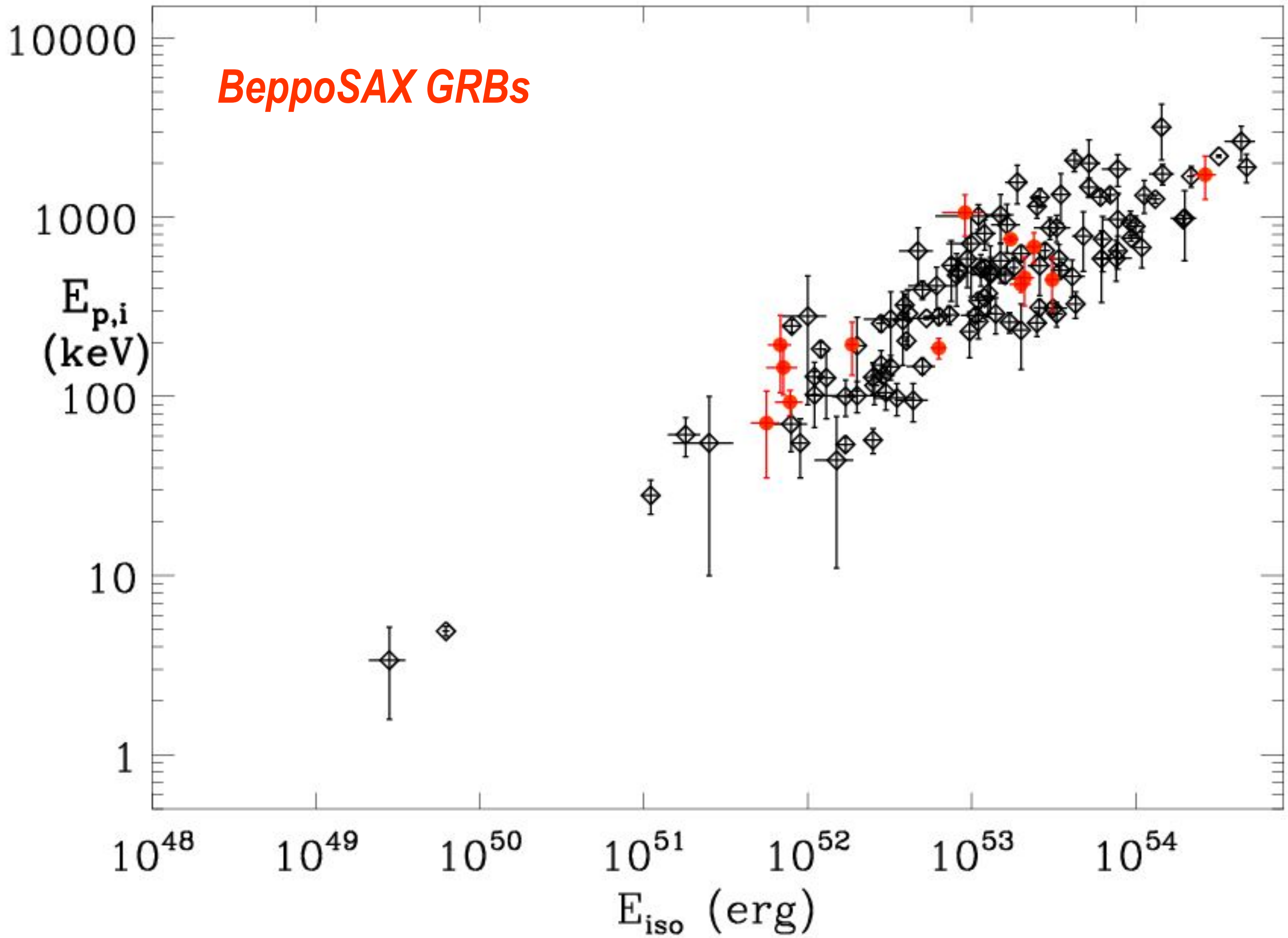
first emphasis given to the discovery, first time called «Amati relation» at BeppoSAX Workshop, Amsterdam, 2003



Further confirmation and extension

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

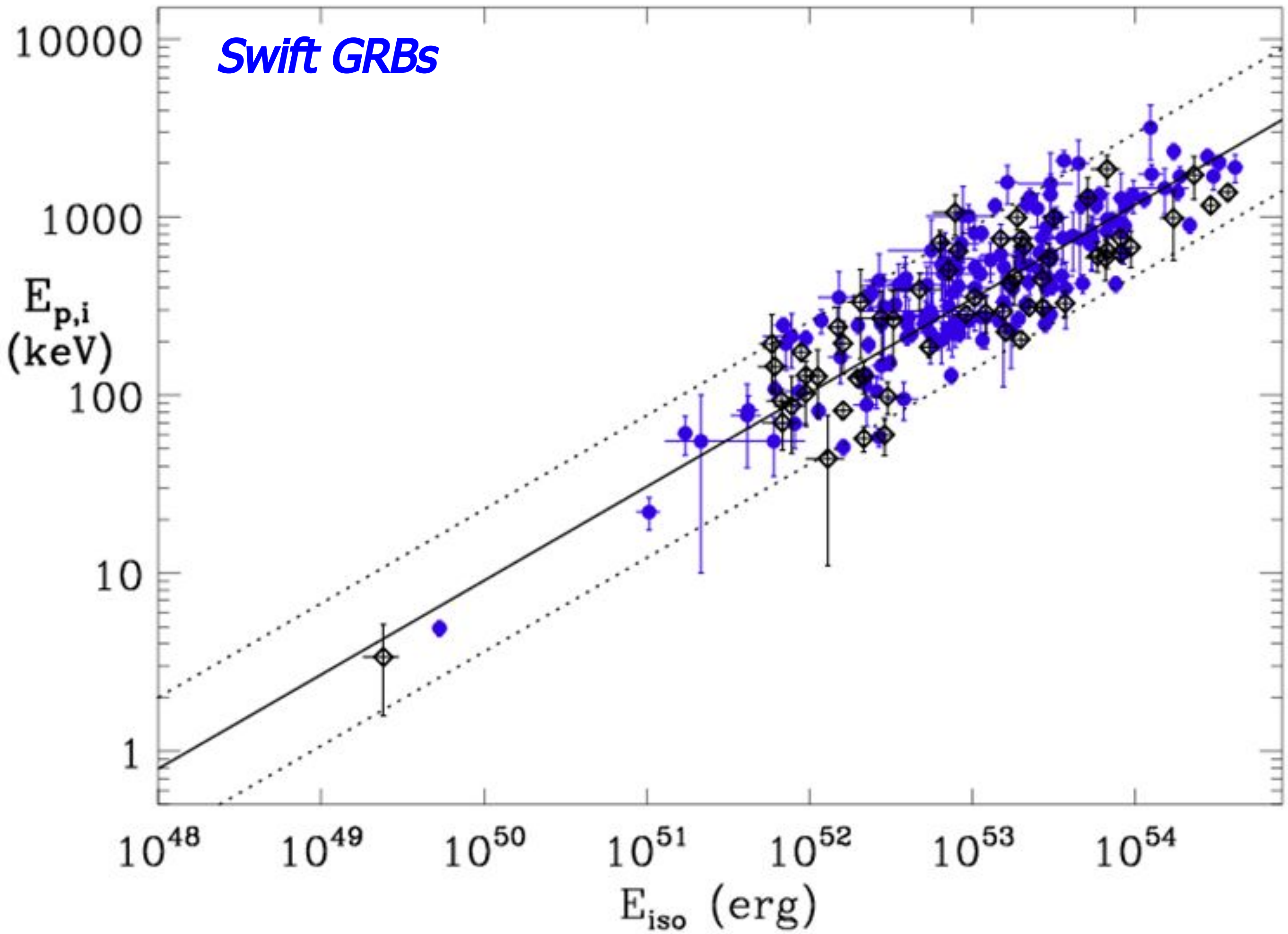
130 long GRBs as of Sept. 2011



Further confirmation and extension

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

212 classical long GRBs as of end 2020

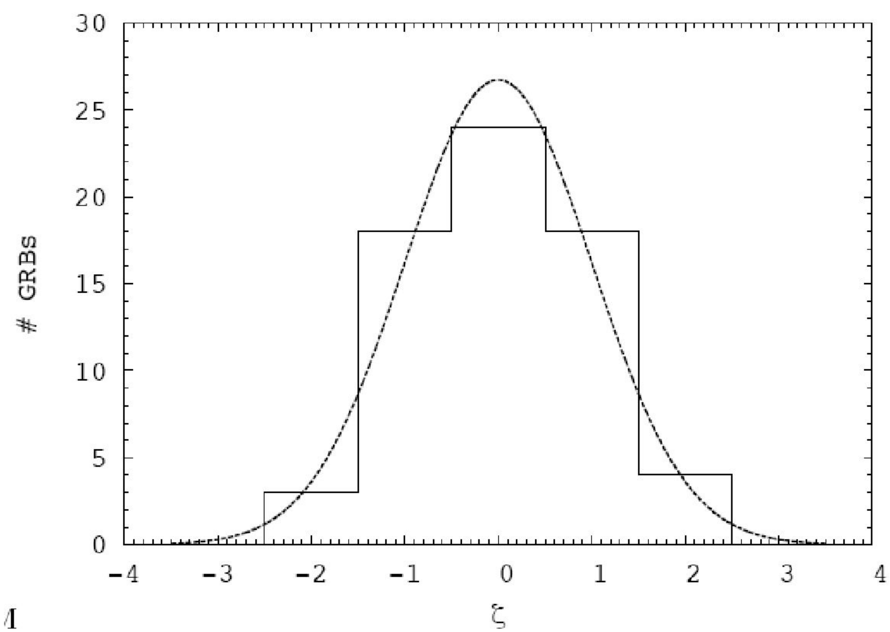


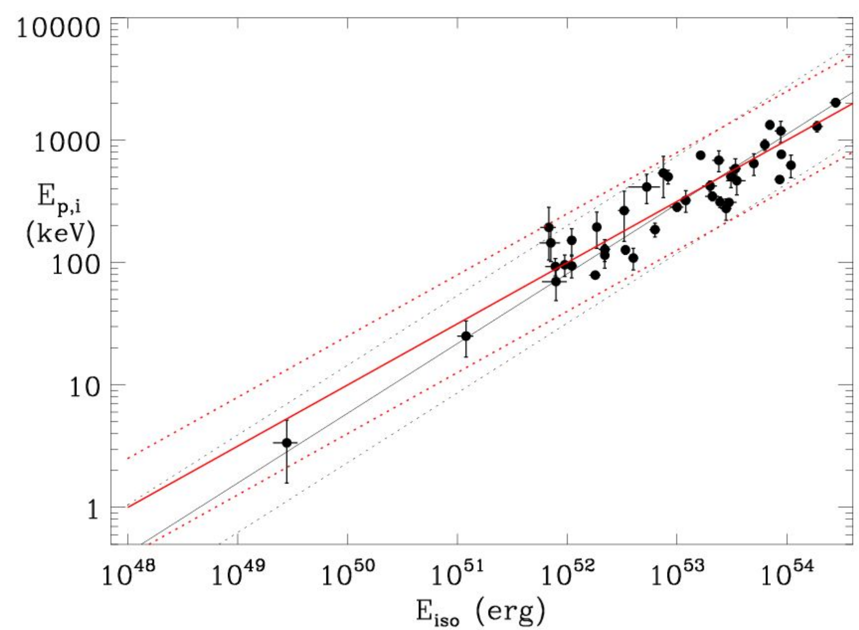
Main properties

- **strong correlation but significant dispersion** of the data around the best-fit power-law; the "extra-statistical scatter" of the data can be quantified by performing a fit whith a max likelihood method which accounts for sample variance and the uncertainties on both X and Y quantities

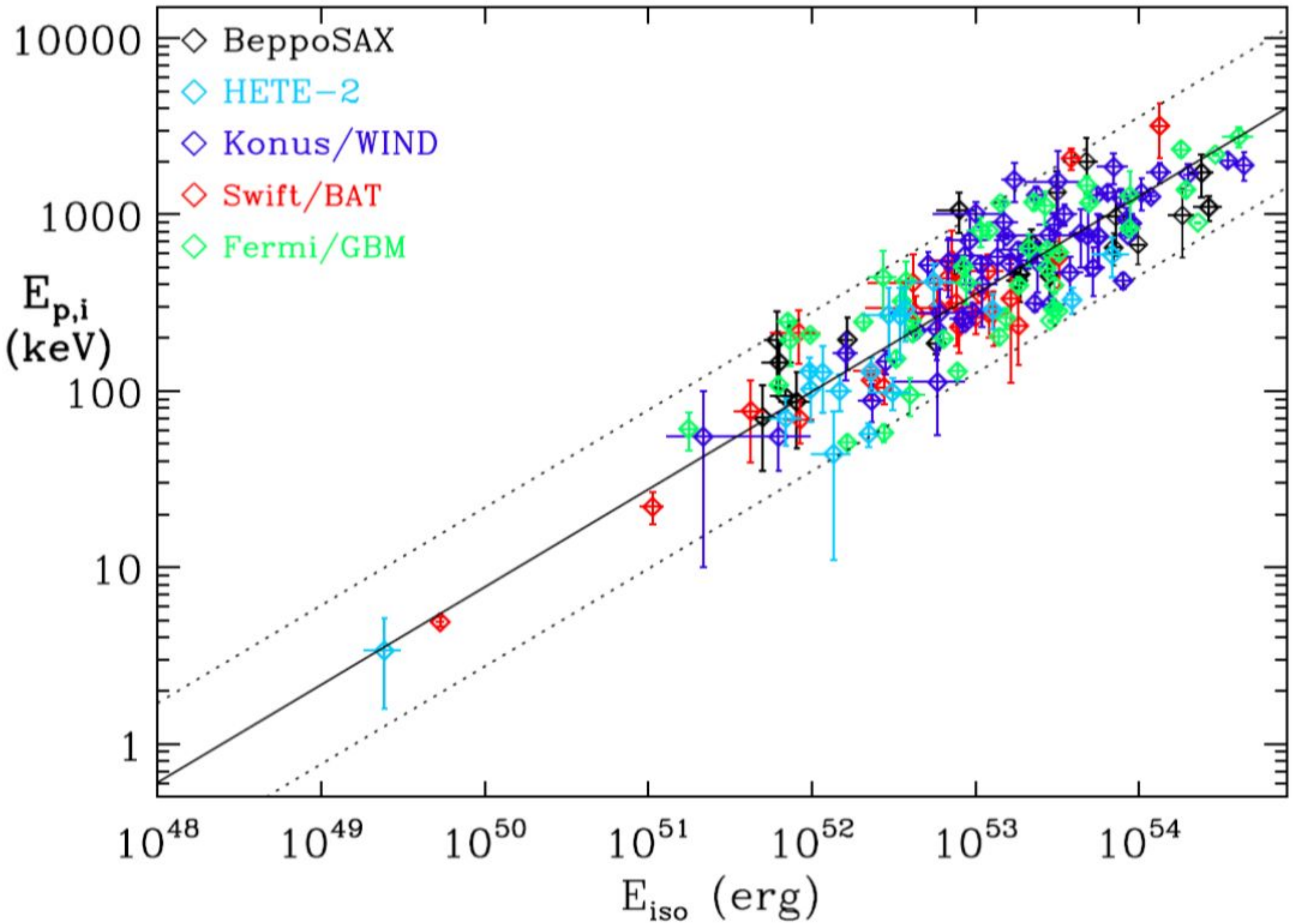
$$L(m, c, \sigma_v ; \boldsymbol{x}, \boldsymbol{y}) = \frac{1}{2} \sum_i \log (\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_{x_i}^2) + \frac{1}{2} \sum_i \frac{(y_i - m x_i - c)^2}{\sigma_v^2 + \sigma_{y_i}^2 + m^2 \sigma_{x_i}^2}$$

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



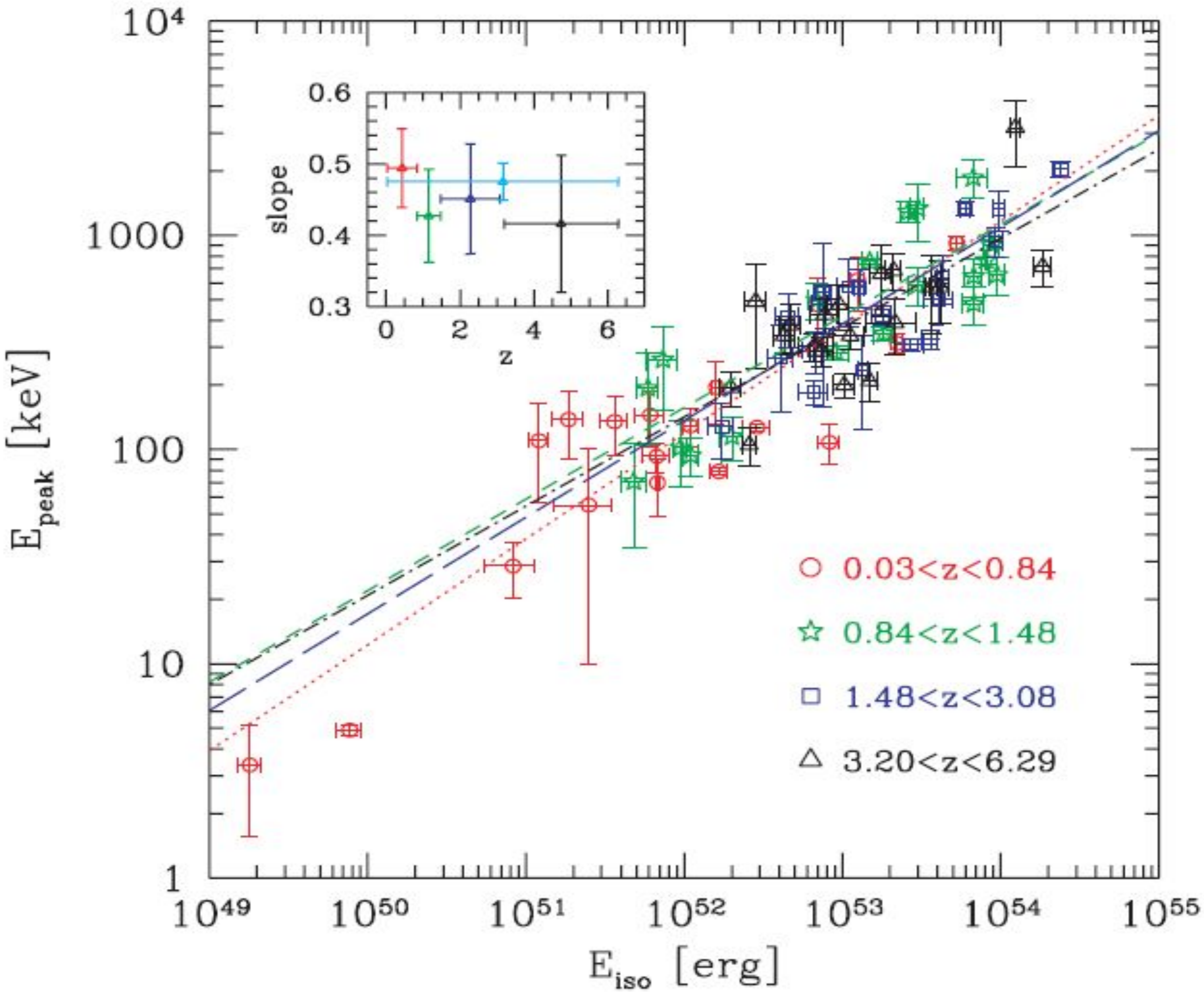


- Amati, Frontera & Guidorzi (2009), Amati & Della Valle (2013: the normalization of the correlation varies only marginally **using GRBs with known redshift** measured by individual instruments with different sensitivities and energy bands



Amati & Della Valle 2013

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



e.g., Ghirlanda et al. 2008

Impact on GRB science

- Physics of GRB prompt emission

- Jet structure and viewing angles

- Identification and understanding of GRB sub-classes

- GRB cosmology

- Other (e.g., redshift discrimination, GRB population

Impact on GRB science

- Amati+02 most cited article on BeppoSAX mission, instruments and data analysis

1 2002A&A...390...81A 2002/07 cited: 1031
Intrinsic spectra and energetics of BeppoSAX Gamma-Ray Bursts with known redshifts
Amati, L.; Frontera, F.; Tavani, M. *and 13 more*

2 1997Natur.387..783C 1997/06 cited: 920
Discovery of an X-ray afterglow associated with the γ-ray burst of 28 February 1997
Costa, E.; Frontera, F.; Heise, J. *and 23 more*

3 1997A&AS..122..299B 1997/04 cited: 641
BeppoSAX, the wide band mission for X-ray astronomy
Boella, G.; Butler, R. C.; Perola, G. C. *and 3 more*

4 2003A&A...399...39R 2003/02 cited: 571
The 2-10 keV luminosity as a Star Formation Rate indicator
Ranalli, P.; Comastri, A.; Setti, G.

Impact on GRB science

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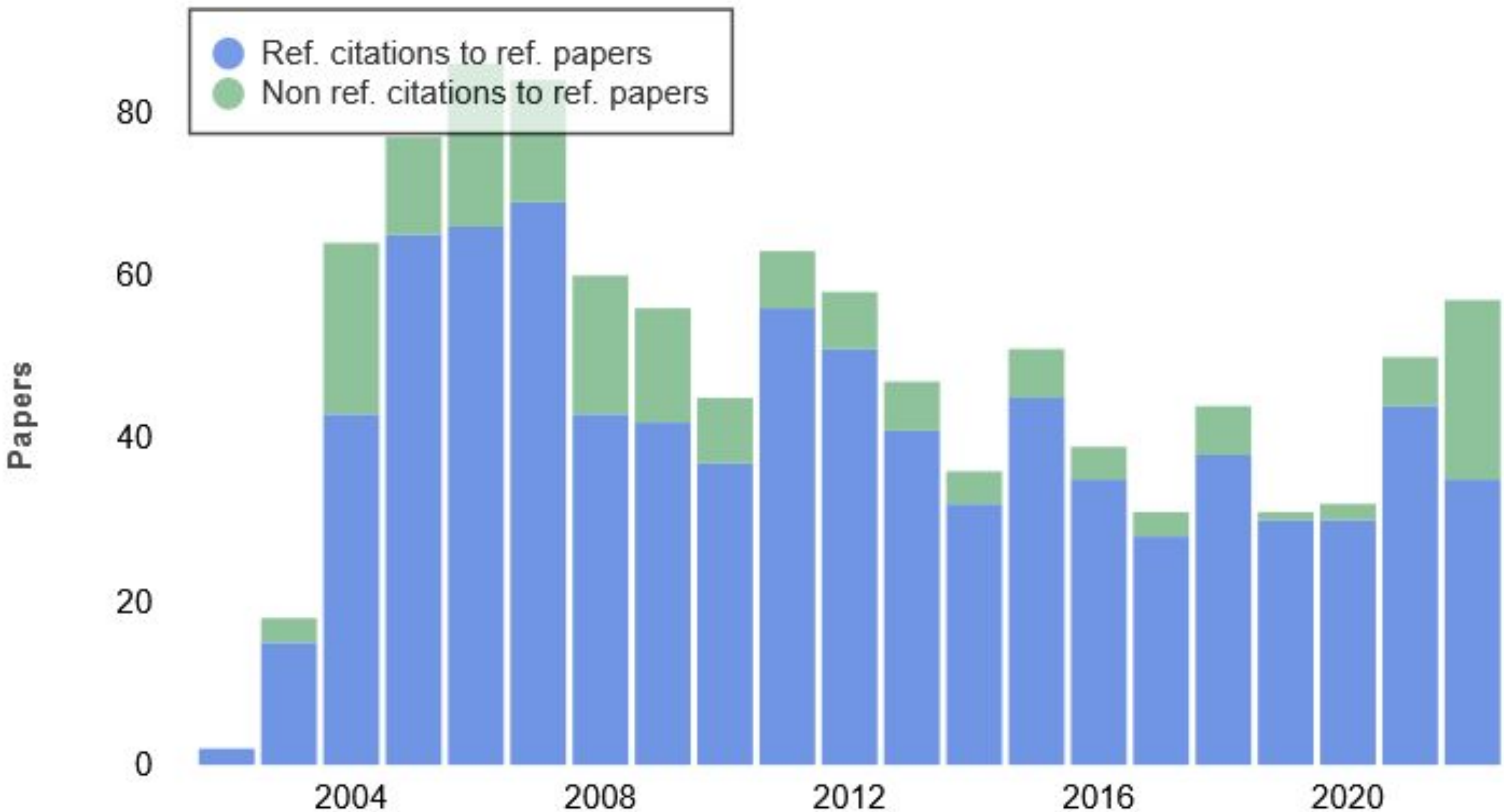


Impact on GRB science

- «Amati relation» included in the title and/or abstract of >170 articles on international refereed journals (>300 total)

1 ☐ 2022ApJ...935....7L 2022/08 cited: 1
Gamma-Ray Burst Constraints on Cosmological Models from the Improved Amati Correlation
Liu, Yang; Liang, Nan; Xie, Xiaoyao *and 3 more*

2 ☐ 2022MNRAS.511.5661Z 2022/04
Testing cosmic anisotropy with the E_p-E_{iso} ('Amati') correlation of GRBs
Zhao, Dong; Xia, Jun-Qing

3 ☐ 2021A&A...651L...8D 2021/07 cited: 6
Redshift evolution of the Amati relation: Calibrated results from the Hubble diagram of quasars at high redshifts
Dai, Yan; Zheng, Xiao-Gang; Li, Zheng-Xiang *and 2 more*

4 ☐ 2013MNRAS.436.308... 2013/12 cited: 18
Pulse-wise Amati correlation in Fermi gamma-ray bursts
Basak, Rupal; Rao, A. R.

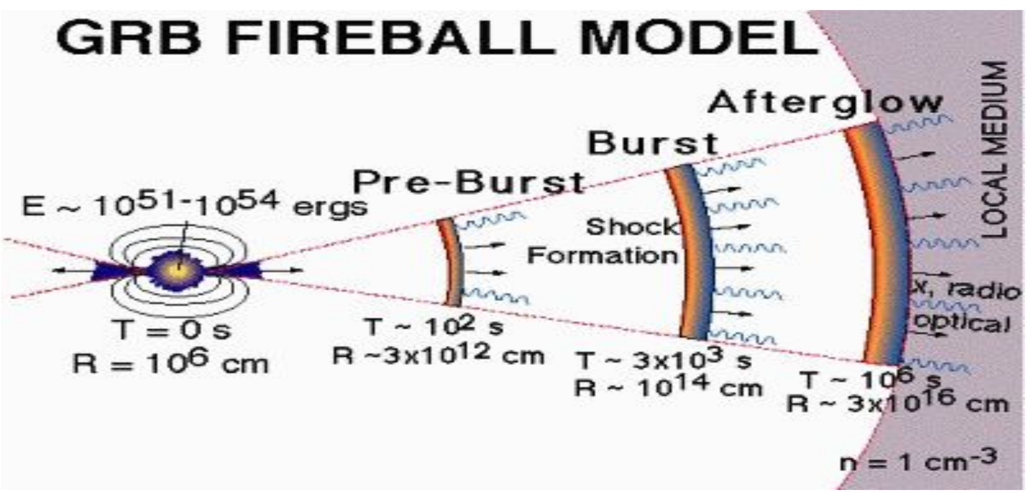
5 ☐ 2013MNRAS.430..163Q 2013/03 cited: 27
Statistical classification of gamma-ray bursts based on the Amati relation
Qin, Yi-Ping; Chen, Zhi-Fu

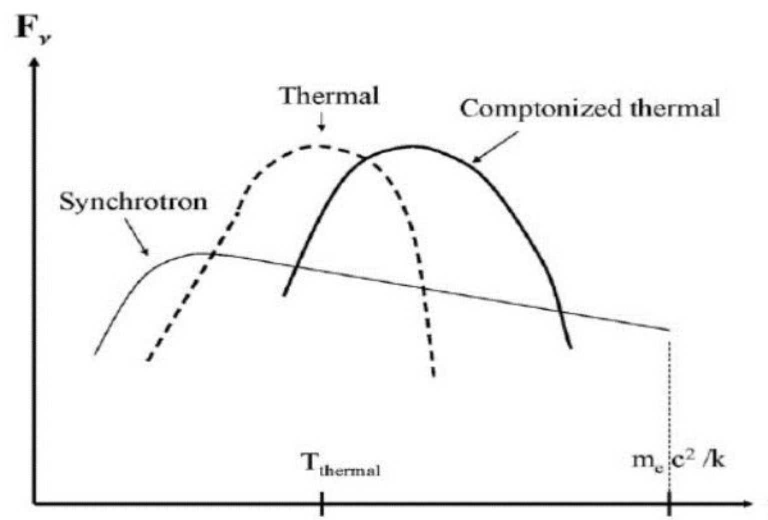
Amati relation: GRB physics

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

- 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)

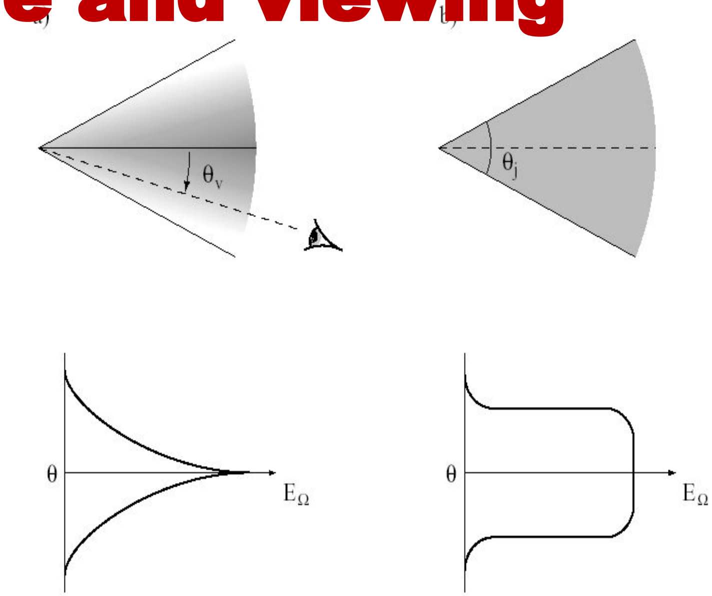


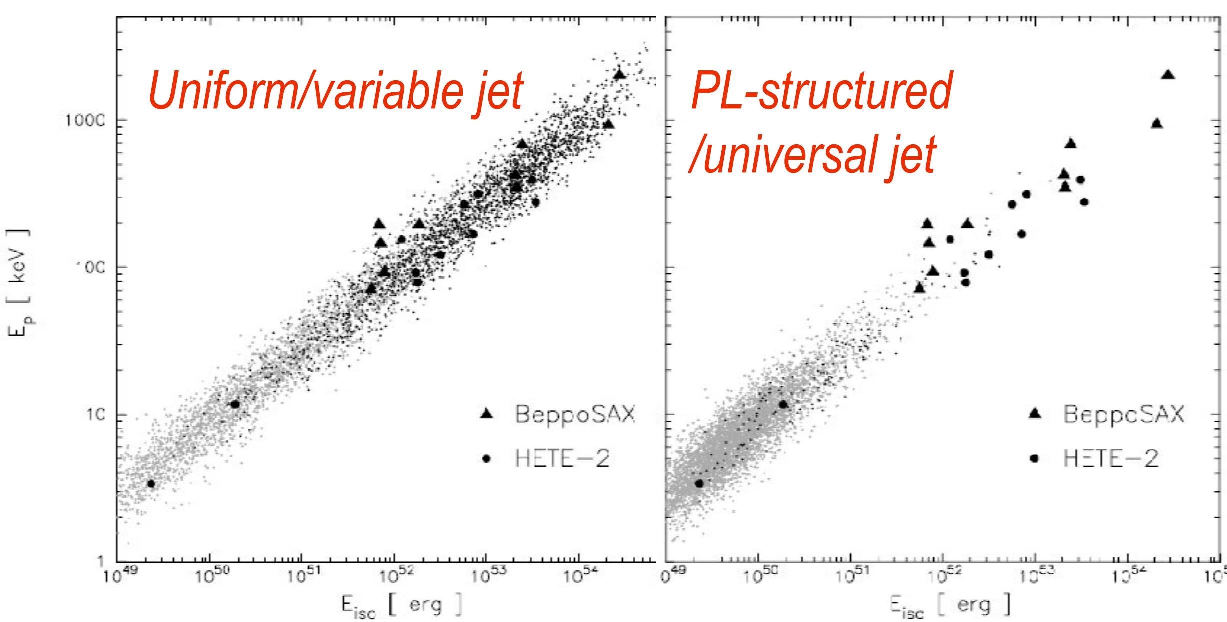


Amati relation: jet structure and viewing angle

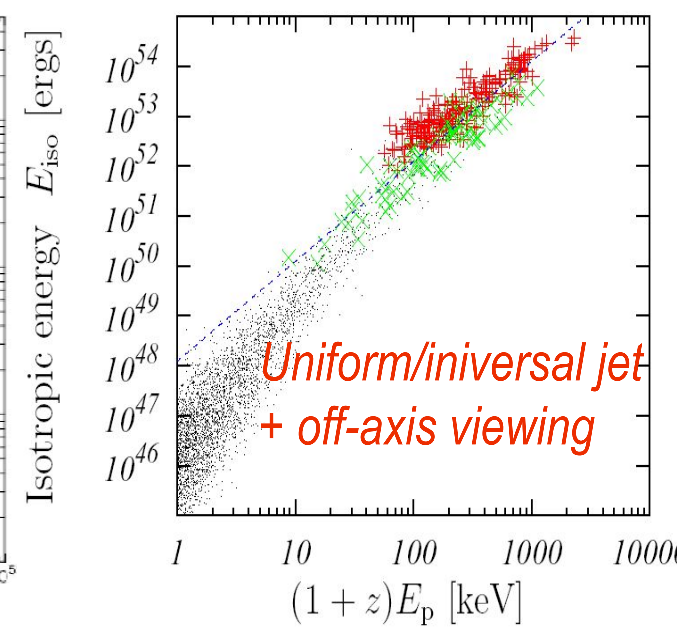
- jet geometry and structure and XRF-GRB unification models (e.g., Lamb et al. 2004)

- 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.)





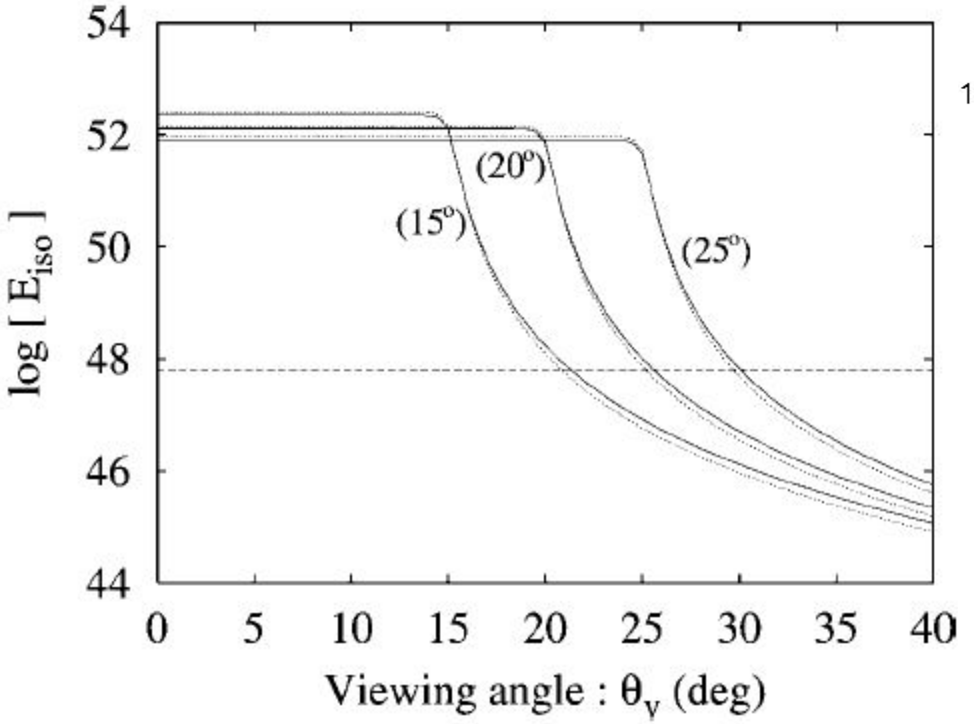
Lamb et al. 2005

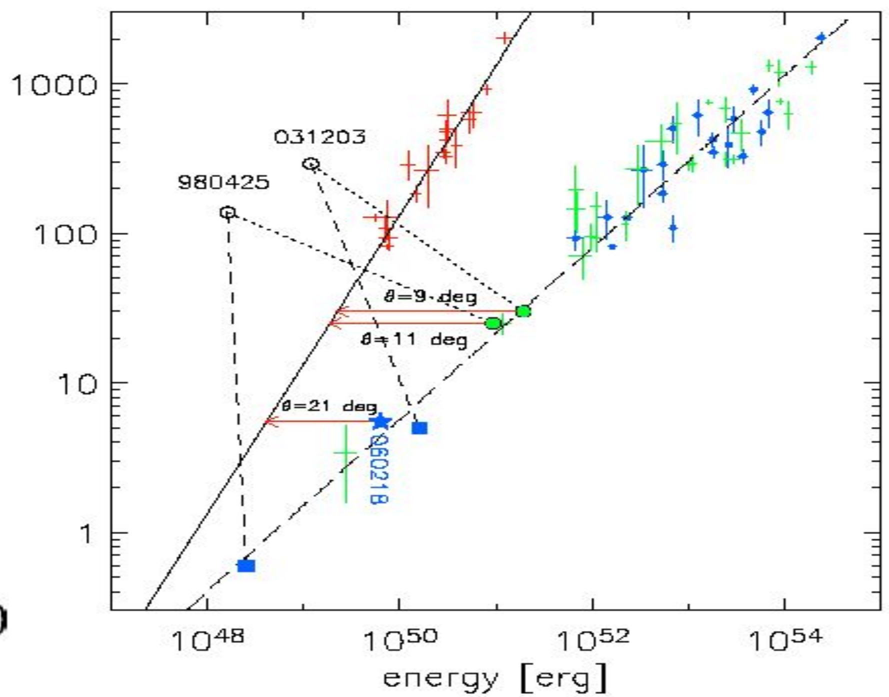


Yamazaki et al. 2004

Amati relation: jet structure and viewing angle

- 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)

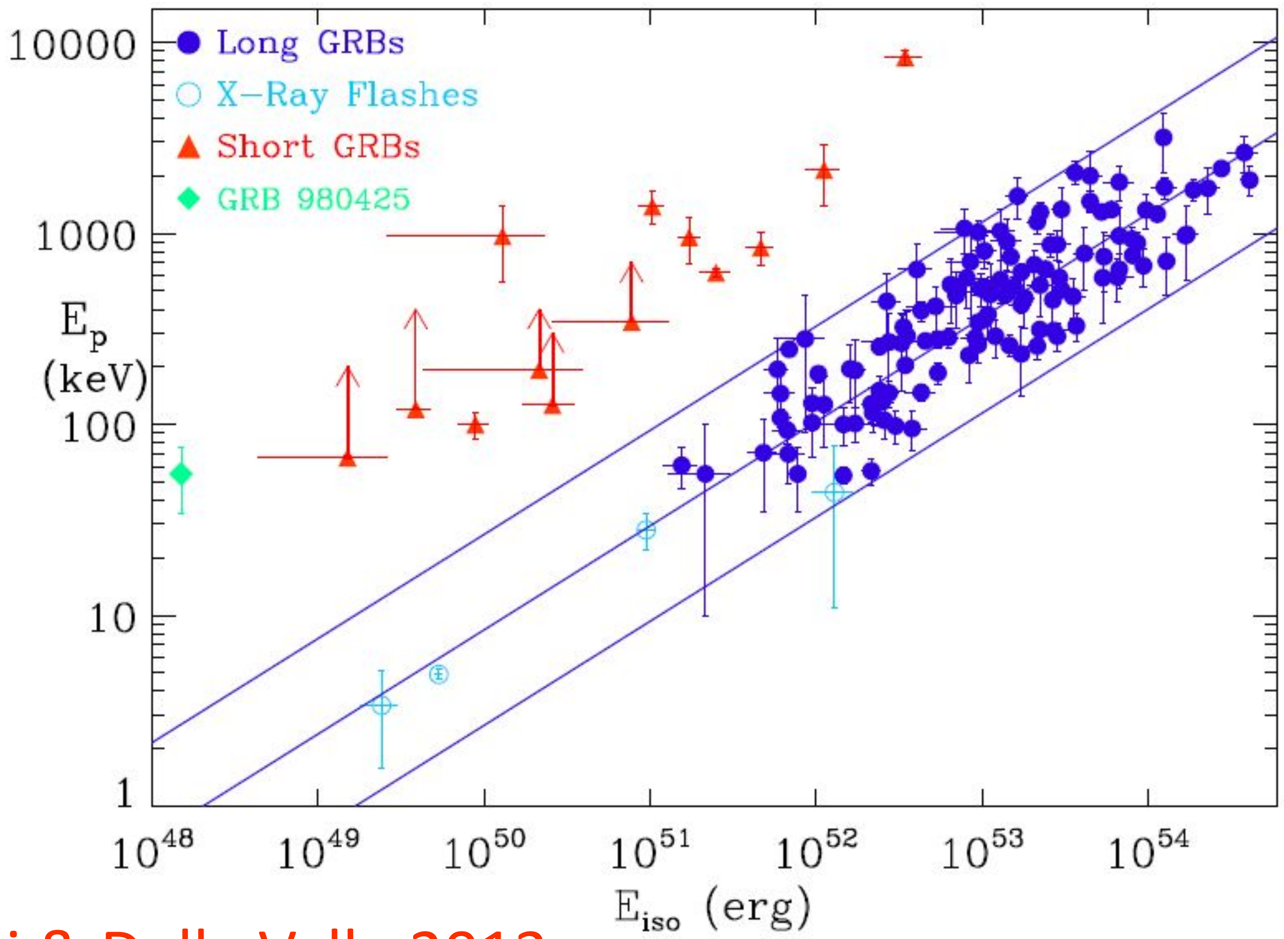




Yamazaki et al., ApJ, 2003

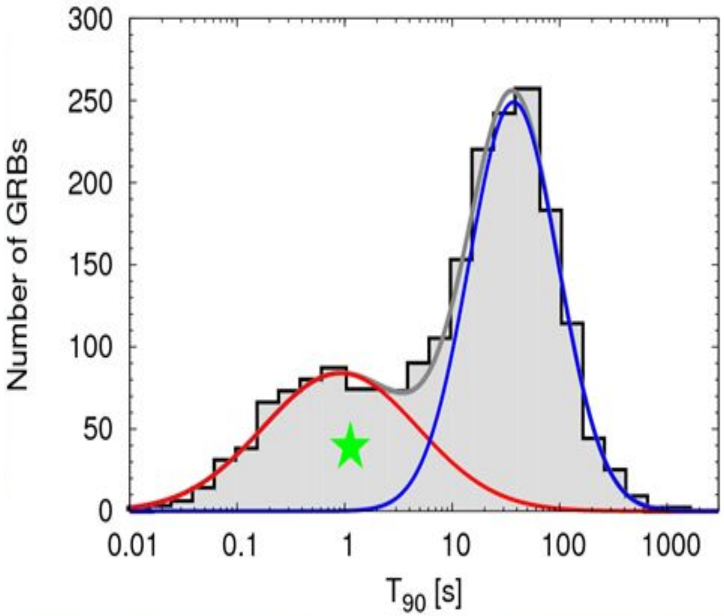
Amati relation: GRB classes

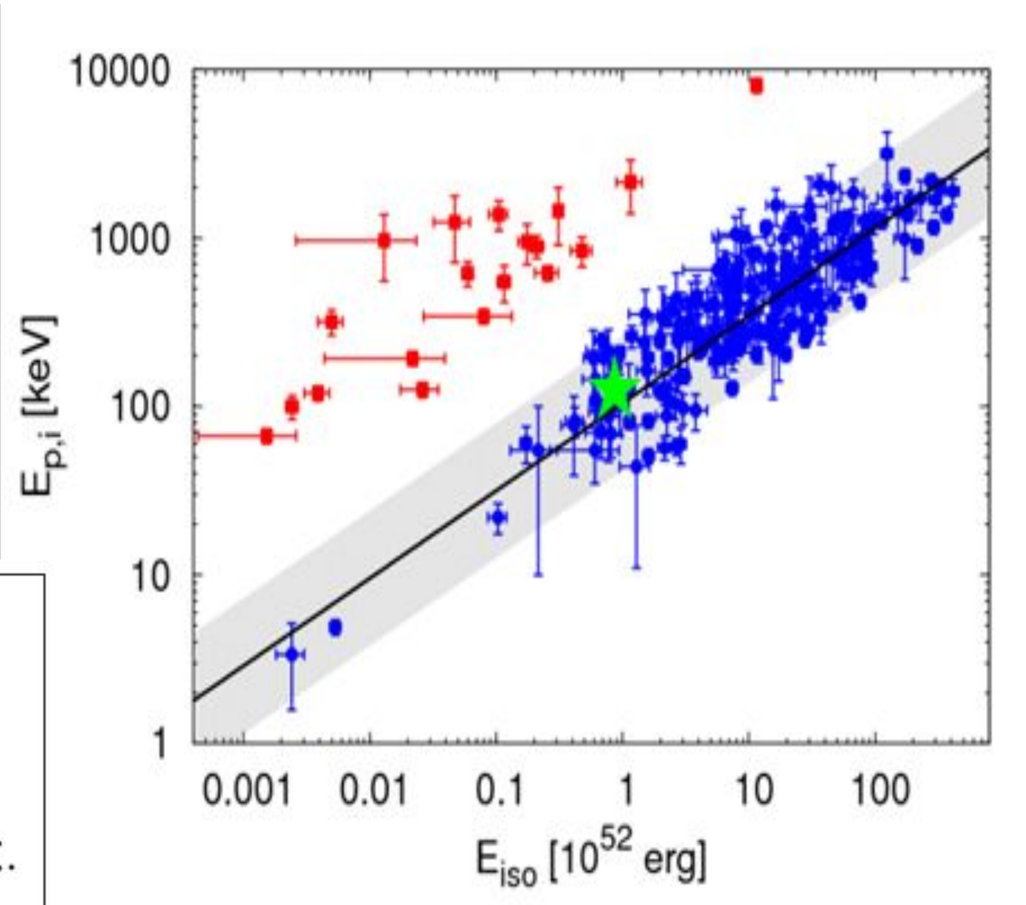
 The Ep,i – Eiso plane and correlation is fundamental for identifying and understanding the origin and physics of different GRB classes

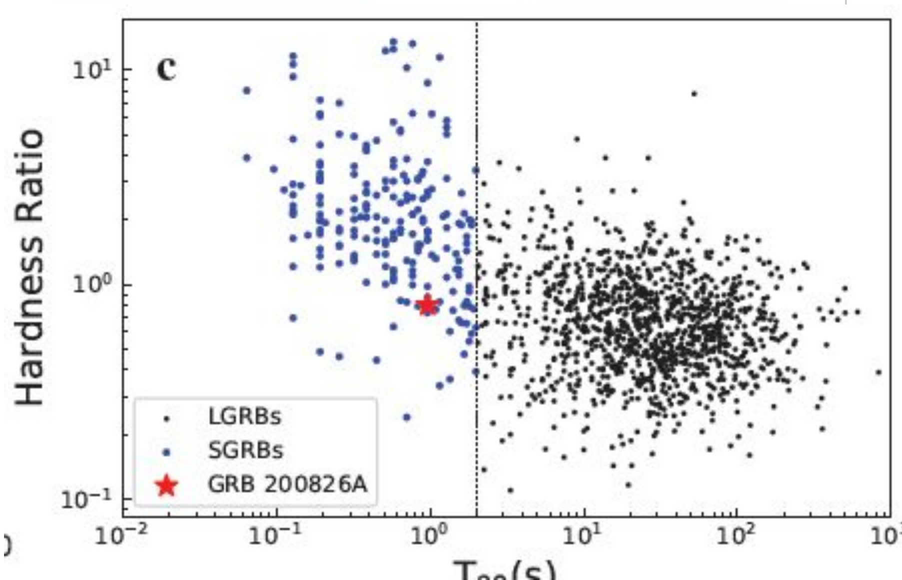


e.g., Amati & Della Valle 2013

Short / long classification: the case *of* GRB 200817A, **a short duration GRB with evidence of association with a SN**







Ahumata et al., Zhang et al., Amati et al., Rossi et al. 2021

Amati relation: GRB classes

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **430,** 163–173 (2013) doi:10.1093/mnras/sts547

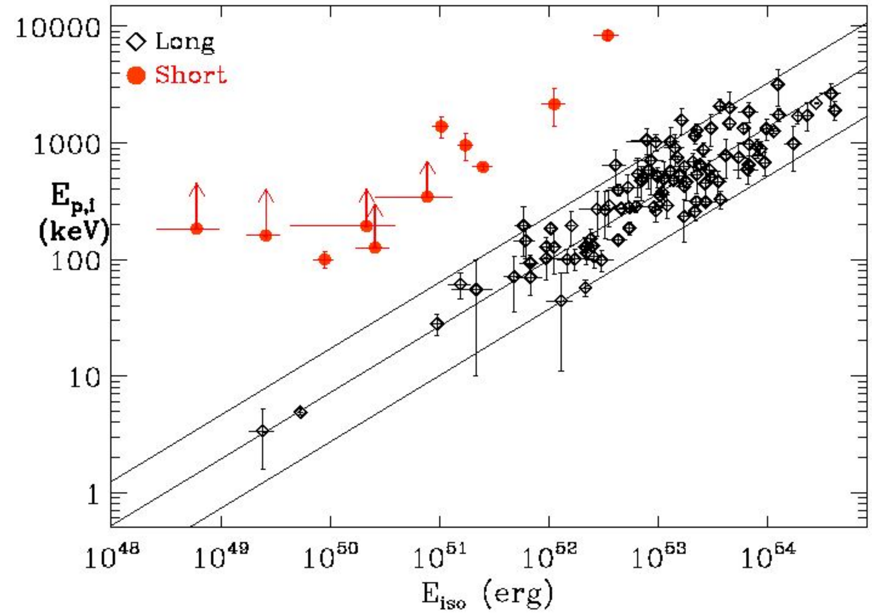
Statistical classification of gamma-ray bursts based on the Amati relation

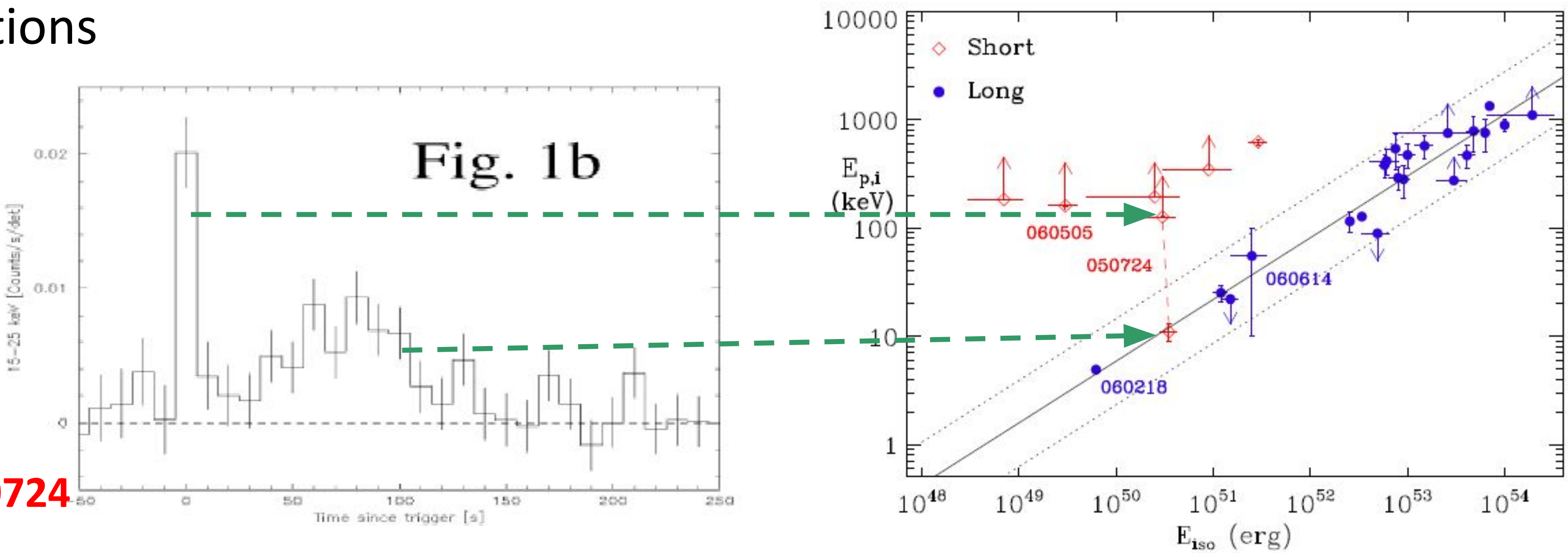
Yi-Ping Qin[1,2,3]★ and Zhi-Fu Chen[1,2]★

this analysis, we propose to statistically classify GRBs in the well-known E_p versus E_{iso} plane with the logarithmic deviation of the E_p value. This classification scheme divides GRBs into two groups: Amati type bursts and non-Amati type bursts. While Amati type bursts follow the Amati relation, non-Amati type bursts do not. It shows that most Amati type bursts are long duration bursts and the majority of non-Amati type bursts are short duration bursts. In addition, it reveals that Amati type bursts are generally more energetic than non-Amati type bursts. An

Short / long classification **and physics**

- 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

Amati relation: GRB cosmology

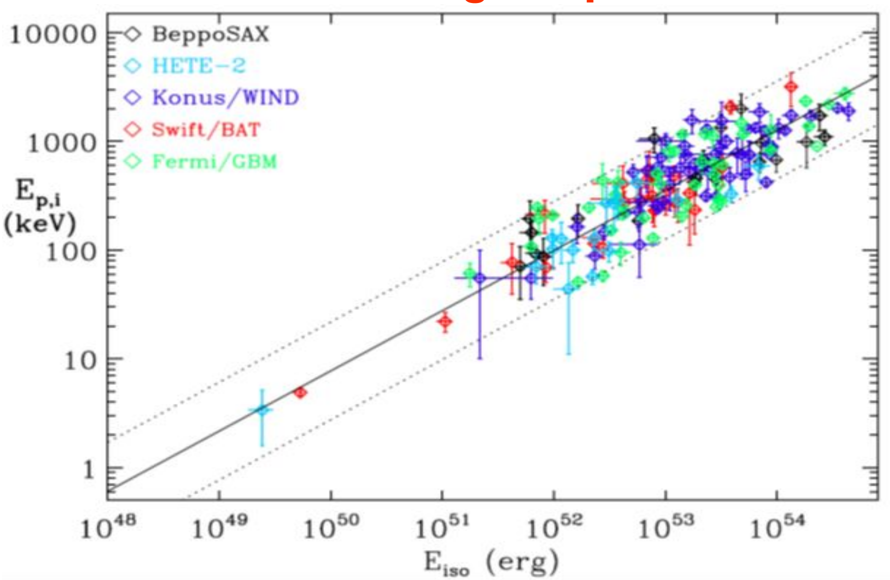
$$E_{p,i} = E_{p,obs} \times (1 + z)$$

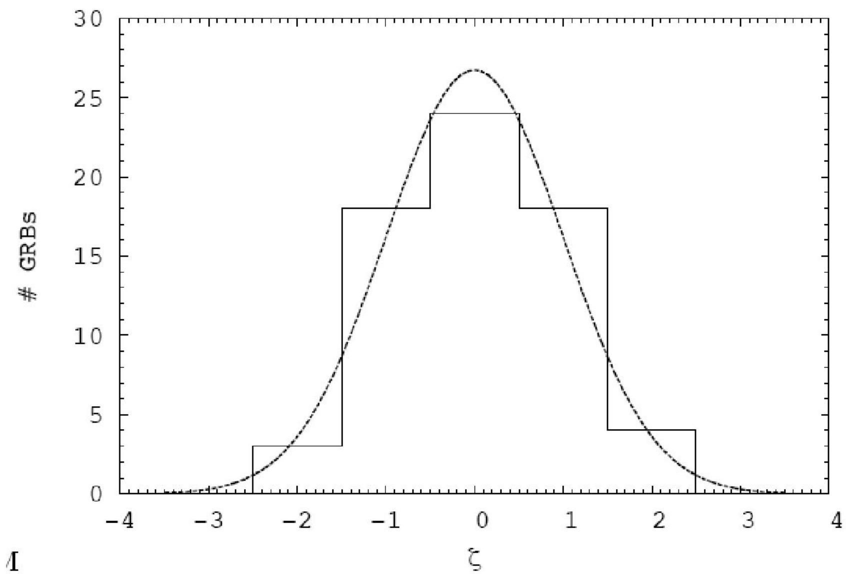
$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \;\; \mathrm{erg}$$

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

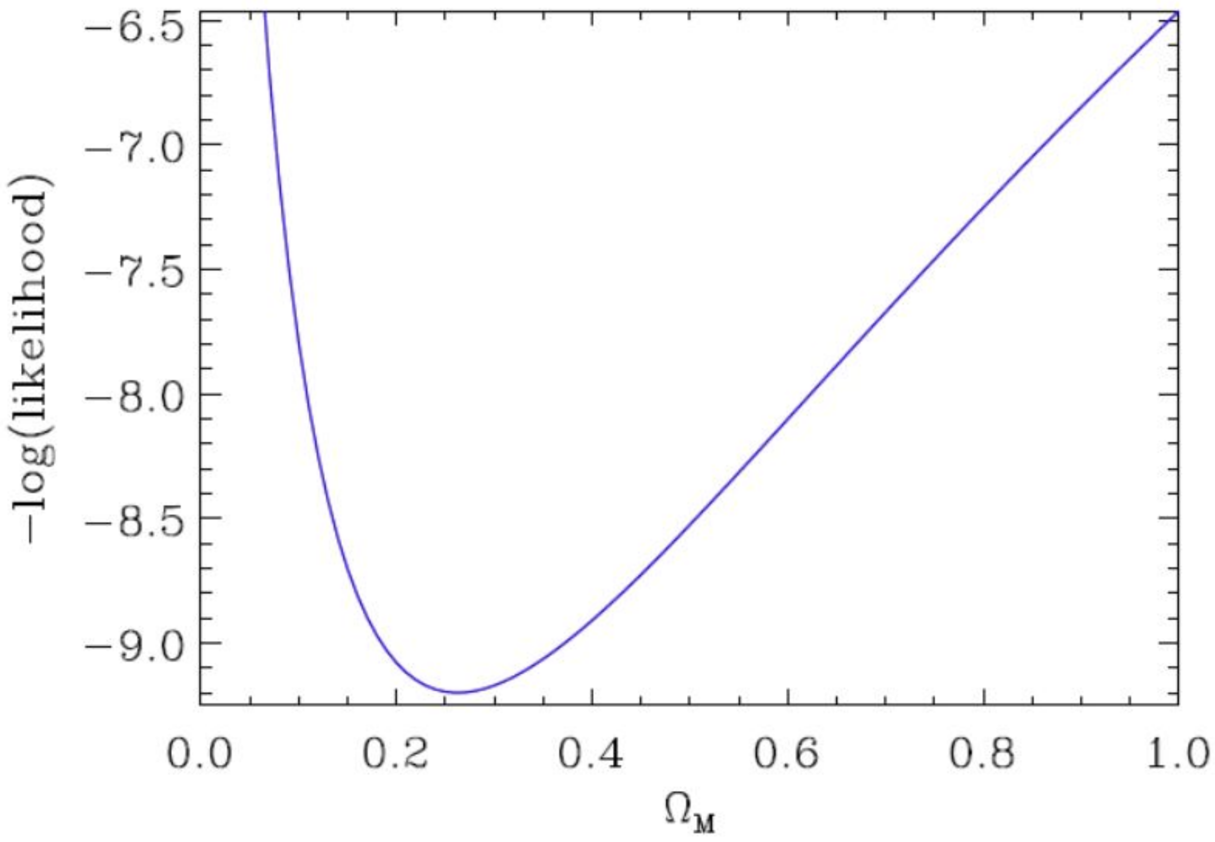
- not enough low-z GRBs for cosmology-independent calibration -> circularity is avoided by fitting simultaneously the parameters of the correlation and cosmological parameters

- does the extrinsic scatter and goodness of fit of the Ep,i-Eiso correlation vary with the cosmological parameters used to compute Eiso ?





- **a fraction of the extrinsic scatter of the $E_{p,i}$-E_{iso} correlation is indeed due to the cosmological parameters used to compute E_{iso}**
- **Evidence, independent on other cosmological probes, that, if we are in a flat Universe , Ω_M is lower than 1 and around 0.3**



Amati et al. 2008, Amati & Della Valle 2013, Moresco, Amati et al. 2022

- 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}
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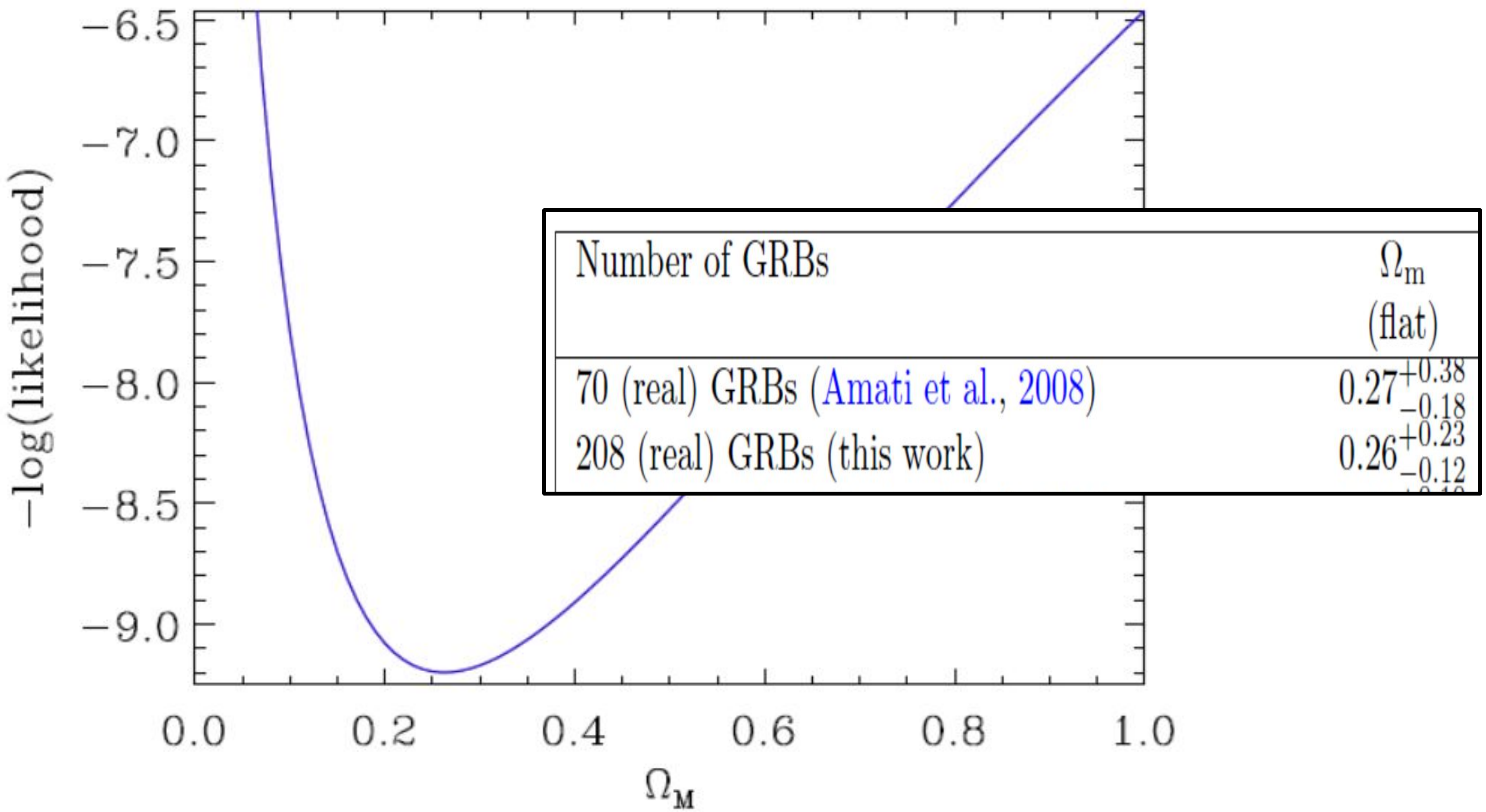
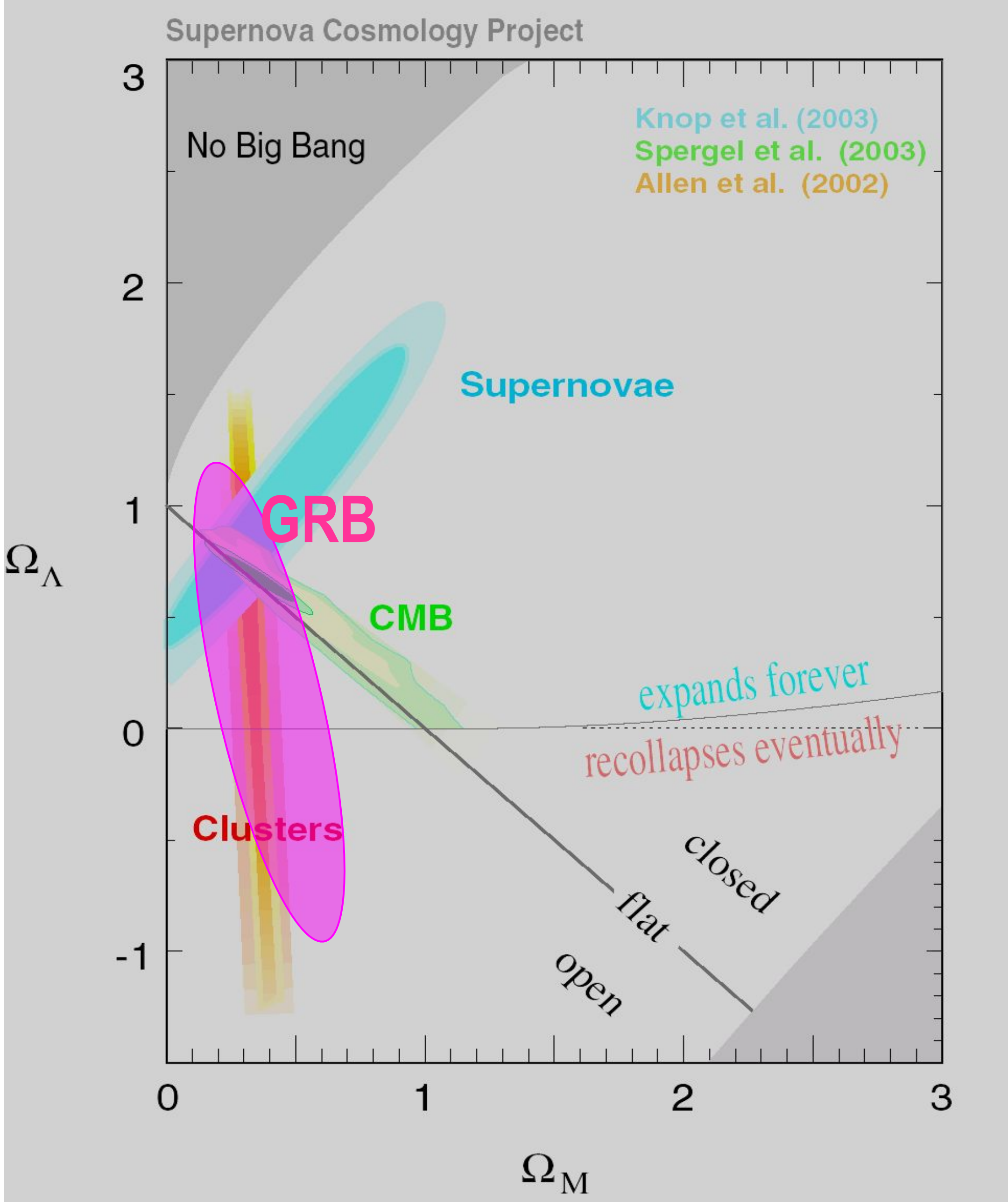
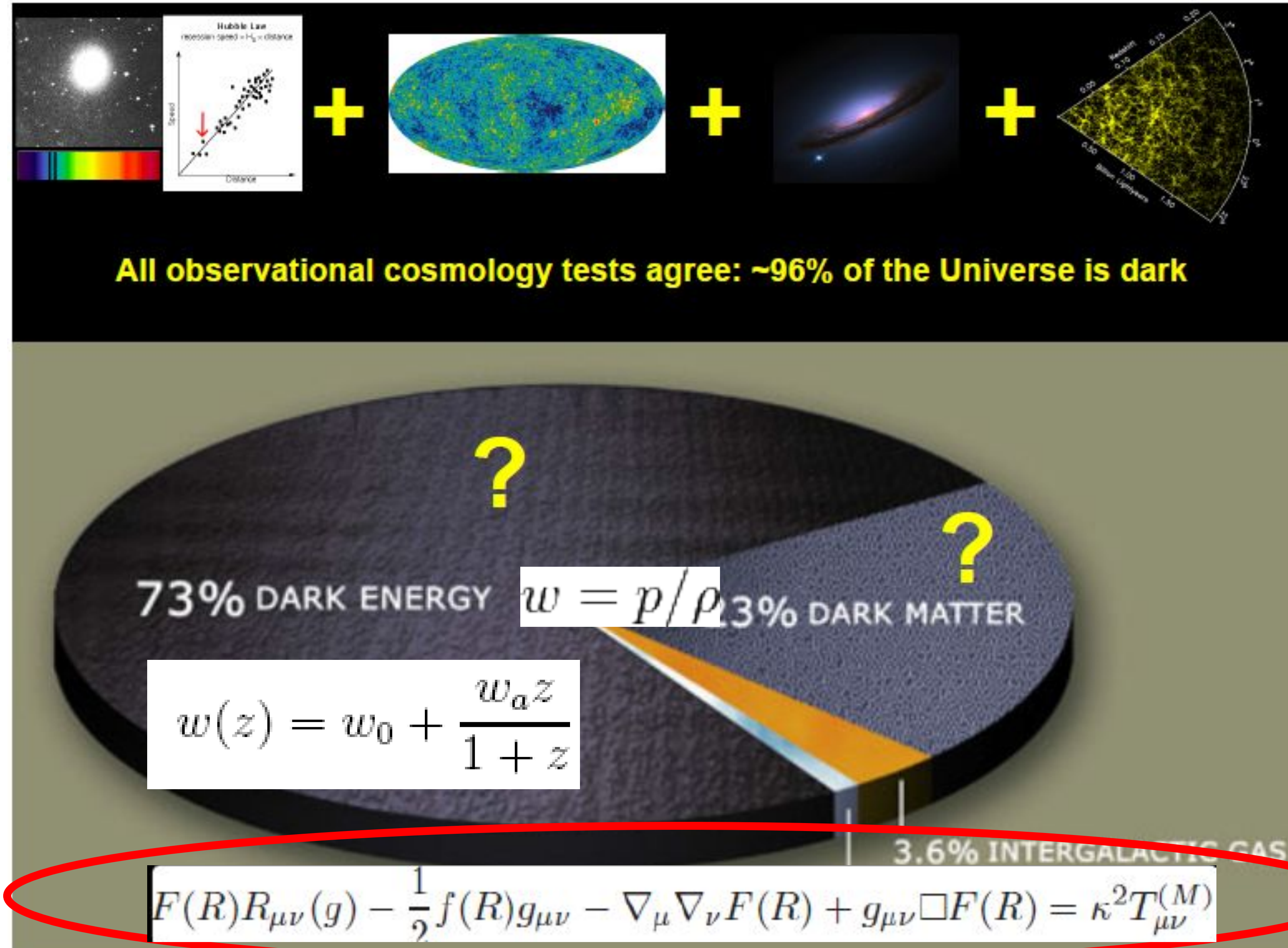


Amati et al. 2008, Amati & Della Valle 2013, Moresco, Amati et al. 2022


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

What we are aiming at ?



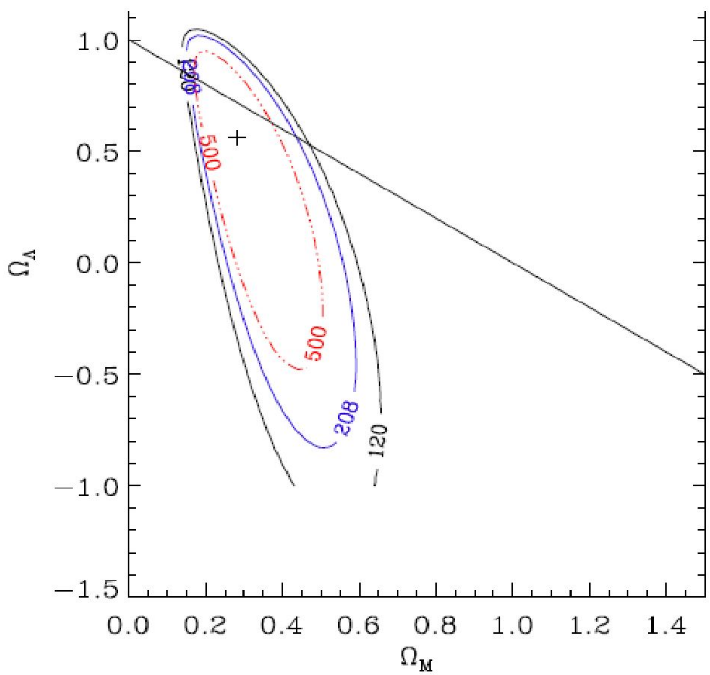
$$w = p/\rho$$

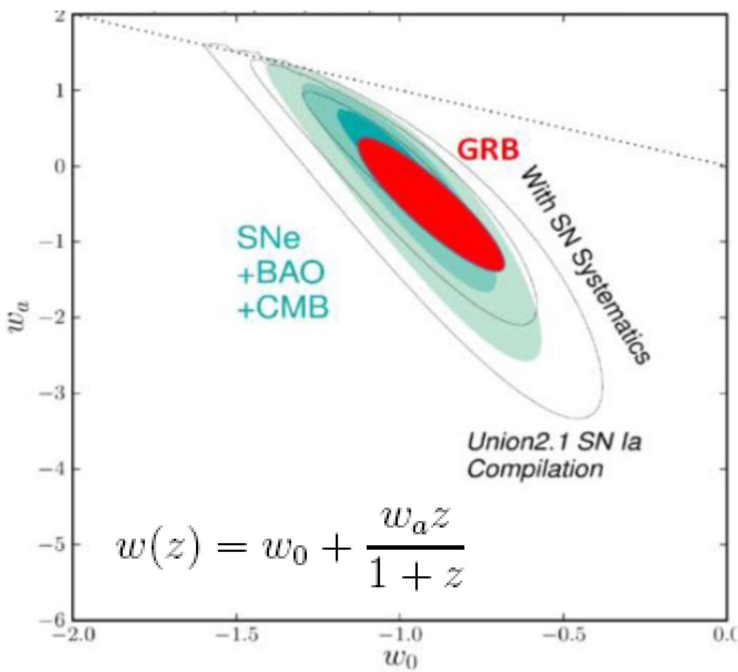
$$w(z) = w_0 + \frac{w_a z}{1+z}$$

$$F(R)R_{\mu\nu}(g) - \frac{1}{2}f(R)g_{\mu\nu} - \nabla_\mu\nabla_\nu F(R) + g_{\mu\nu}\Box F(R) = \kappa^2 T^{(M)}_{\mu\nu}$$

- Future GRB experiments (e.g., **SVOM, HERMES, THESEUS**, …) and more investigations (**e.g., reliable estimates of jet angles and self-calibration**) will improve the significance and reliability of the results and allow to go beyond SN Ia cosmology (e.g. investigation of dark energy)

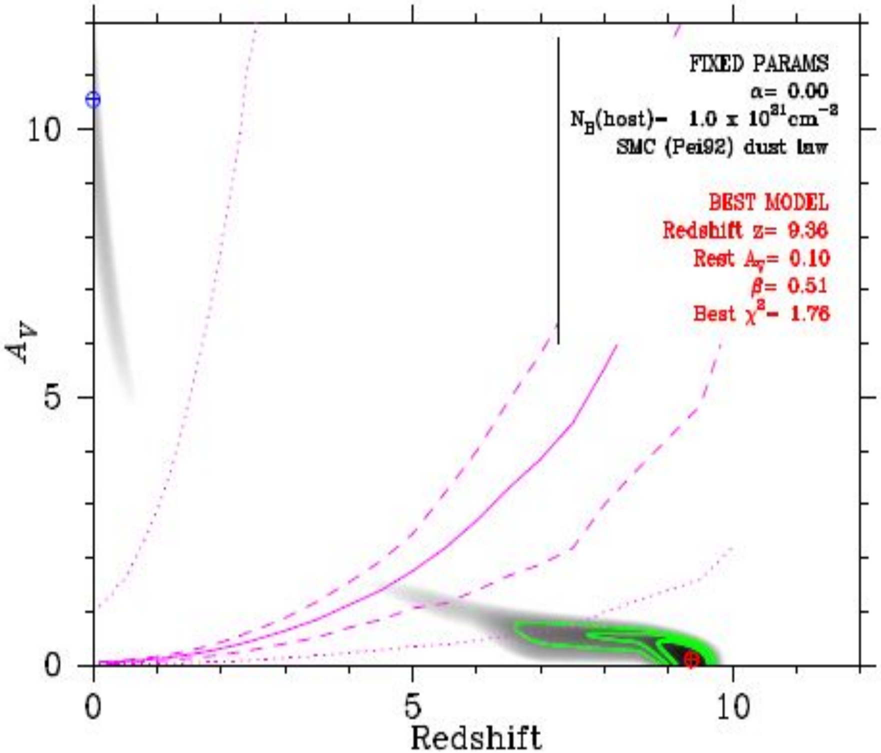
Number of GRBs	Ω_m (flat)	w_0 (flat, Ω_m=0.3,w_a=0.5)
70 (real) GRBs (Amati et al., 2008)	$0.27^{+0.38}_{-0.18}$	<-0.3 (90%)
208 (real) GRBs (this work)	$0.26^{+0.23}_{-0.12}$	$-1.2^{+0.4}_{-1.1}$
500 (208 real + 292 simulated) GRBs	$0.29^{+0.10}_{-0.09}$	$-0.9^{+0.2}_{-0.8}$
208 (real) GRBs, calibration	$0.30^{+0.06}_{-0.06}$	$-1.1^{+0.25}_{-0.30}$
500 (208 real + 292 simulated) GRBs, calibration	$0.30^{+0.03}_{-0.03}$	$-1.1^{+0.12}_{-0.15}$

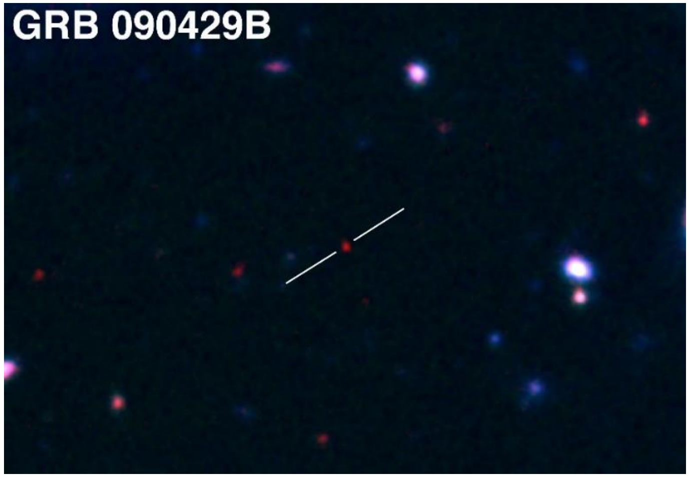


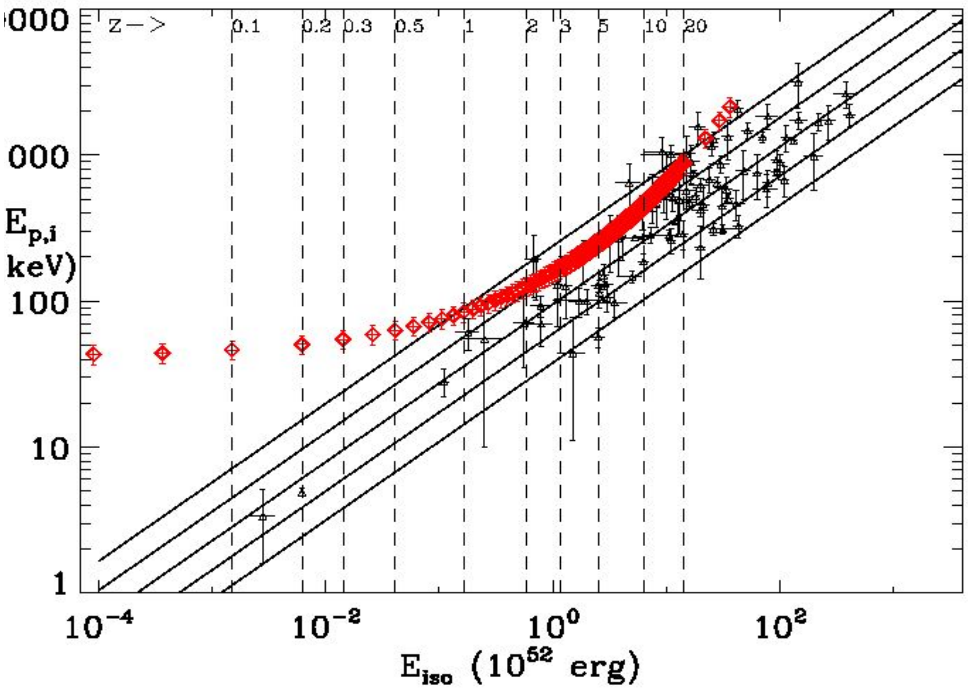


Amati relation: redshift discrimination

The case of GRB 090429B: **confirmation of the photometric redshift of ~9.4 !** (Cucchiara et al. 2011)







Summary

- Discovered in 2002 by Amati et al., the Ep,i - Eiso correlation in Gamma-Ray Bursts **is the BeppoSAX result with the highest impact in scientific literature**, outshining even the discovery of X-ray afterglow

- After 20 years, the Ep,i – Eiso correlation (“Amati” relation”) **is still one of the most investigated and used properties of GRBs**, with fundamental implications for prompt emission physics, jest structure and viewing angle, GRB sub-classes, GRB cosmology and more

- Next generation space missions dedicated to GRBs, first of all **SVOM, then HERMES and, hopefully, a THESEUS-like mission,** and improved technicques and methods (self-calibration, jet opening angles, spectral components, physical grounds, combination with other observables, …) **will allow to further test, extend and fully exploit the correlation**

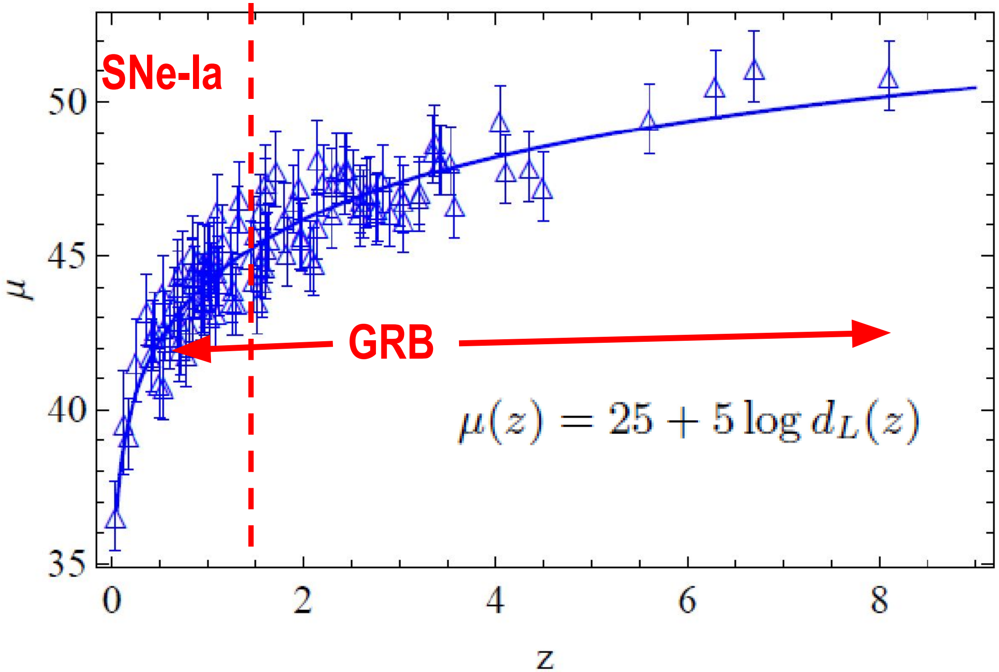
Back-up slides

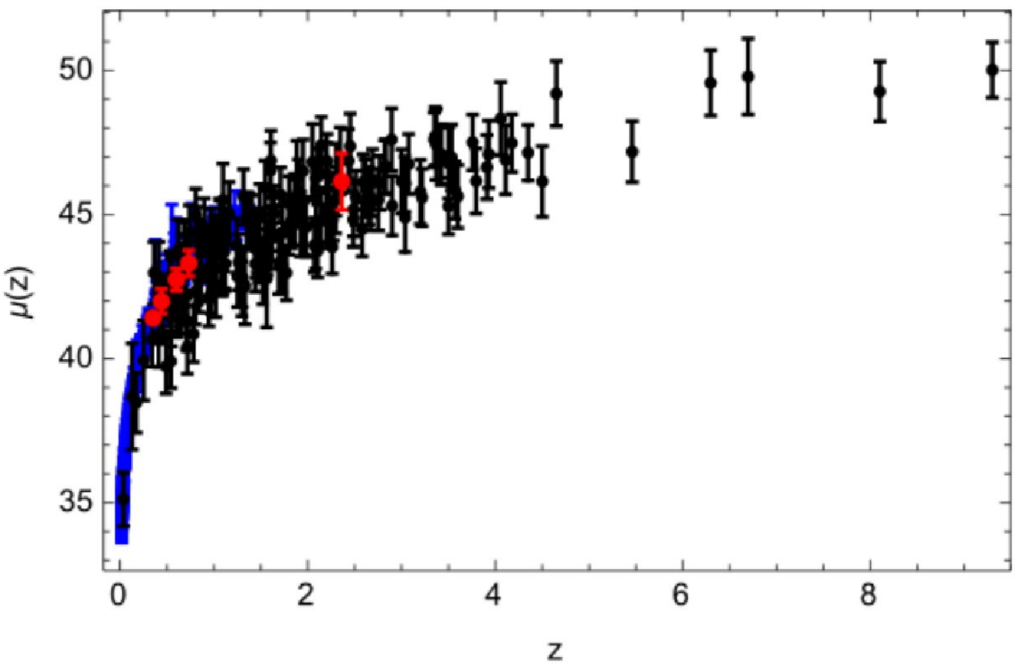
❑ Calibration with SNe-Ia

- The GRB Hubble diagram extends to much higher z w/r to SNe Ia

- **The GRB Hubble diagram is consistent with SNe Ia Hubble diagram and BAO points at low redshifts: reliability**

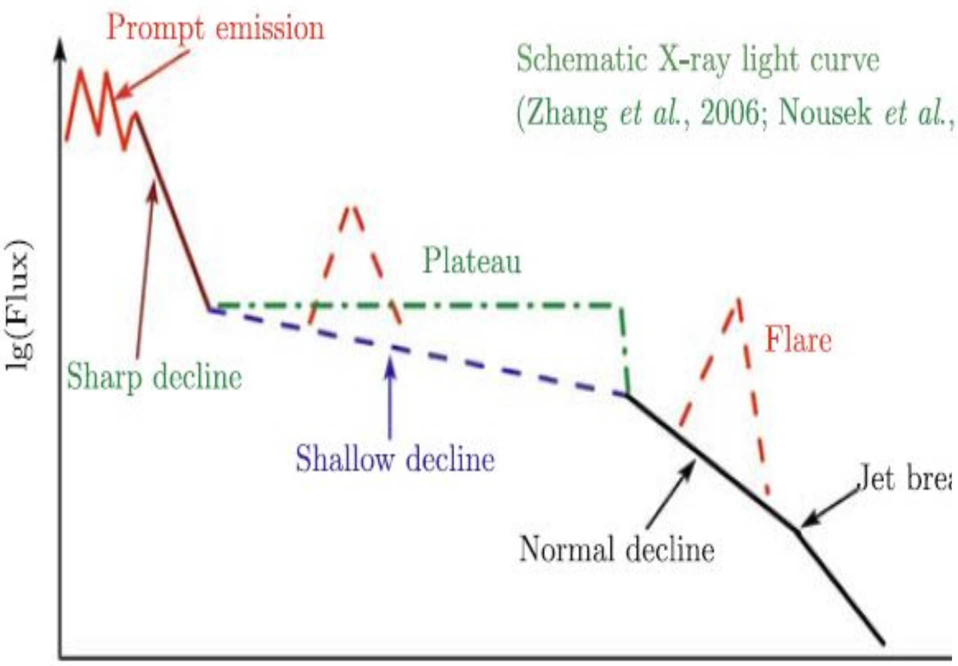
- e.g., Capozziello et al., Kodama et al., Tsutsui et al., Demianski et al.):





❑ Involving other GRB observables

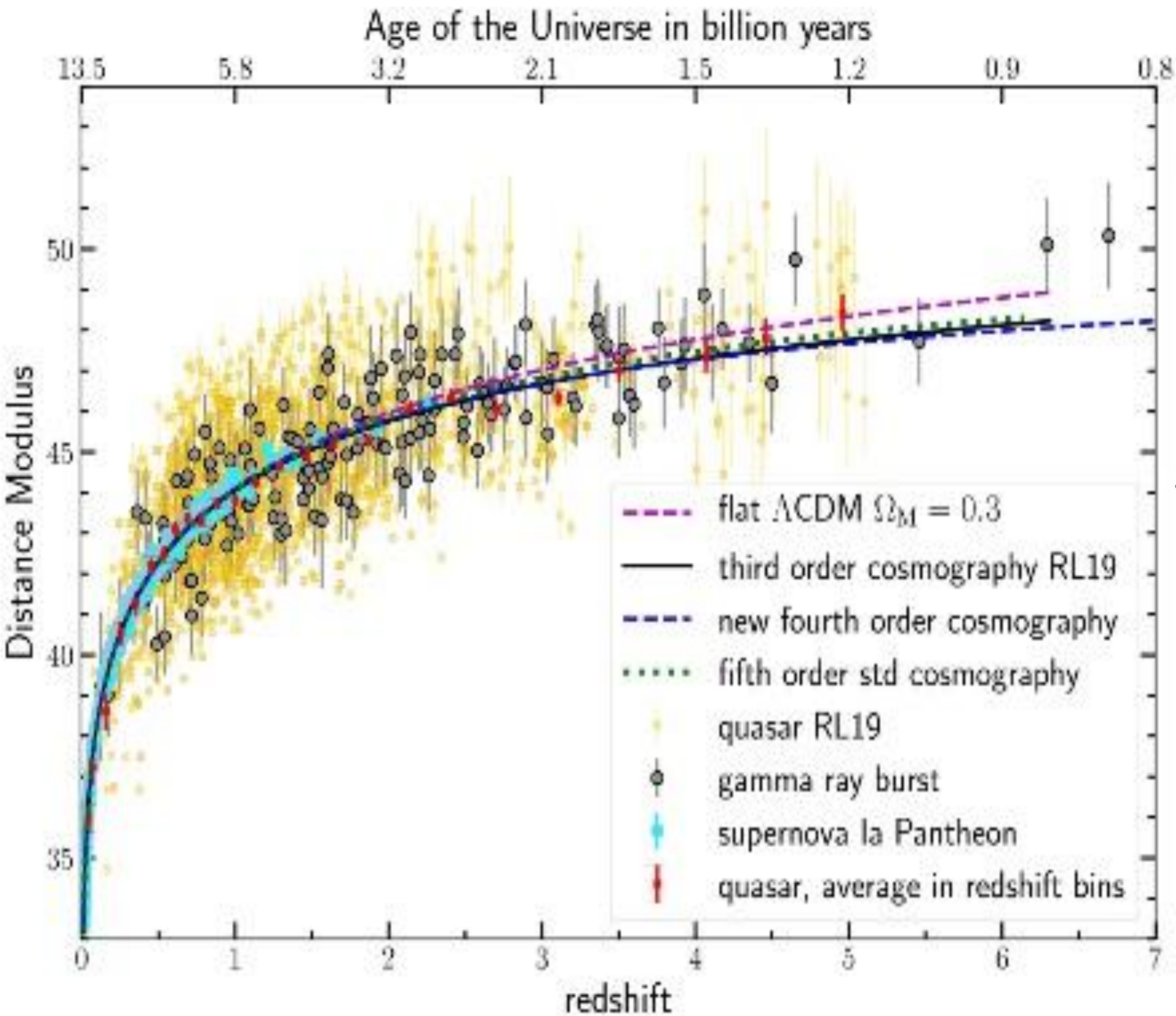
- Extending or replacing the Ep-Intensity correlation by involving other prompt or afterglow properties: e.g., "Combo relation" (Izzo et al., Muccino et al.) , **Lx-Ta and Lx-Ta-Lp relations (Dainotti et al.)**

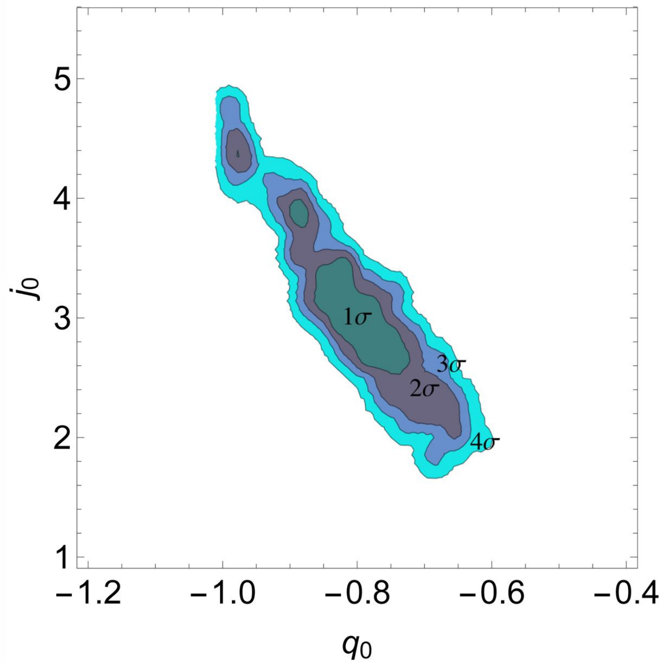


Correlation	Reference
$E_{p,i}$–E_{iso}	Amati et al. (2002)
$E_{p,i}$– E_{γ}	Ghirlanda et al. (2004)
$E_{p,i}$–L_{iso}	Yonetoku et al. (2004)
$L_{peak} - \tau_{lag}$	Azzam (2012)
$L_{iso} - V$	Fenimore and Ramirez-Ruiz (2000)
$L_{iso} - E_{p,i} - T_{0.45}$	Firmani et al. (2006)
$L_{iso} - E_{p,i} - t_{break}$	Liang and Zhang (2005)
$L_X - T_a$	Dainotti et al. (2008)
$E_{X,iso} - E_{\gamma,iso} - E_{pk}$	Bernardini et al. (2012)
$E_{\gamma,iso} - E_{X,iso} - E_{pk}$	Izzo et al. (2015)

Moresco et al. 2022

❑ Joining GRBs with other probes: e.g., high-z GNs

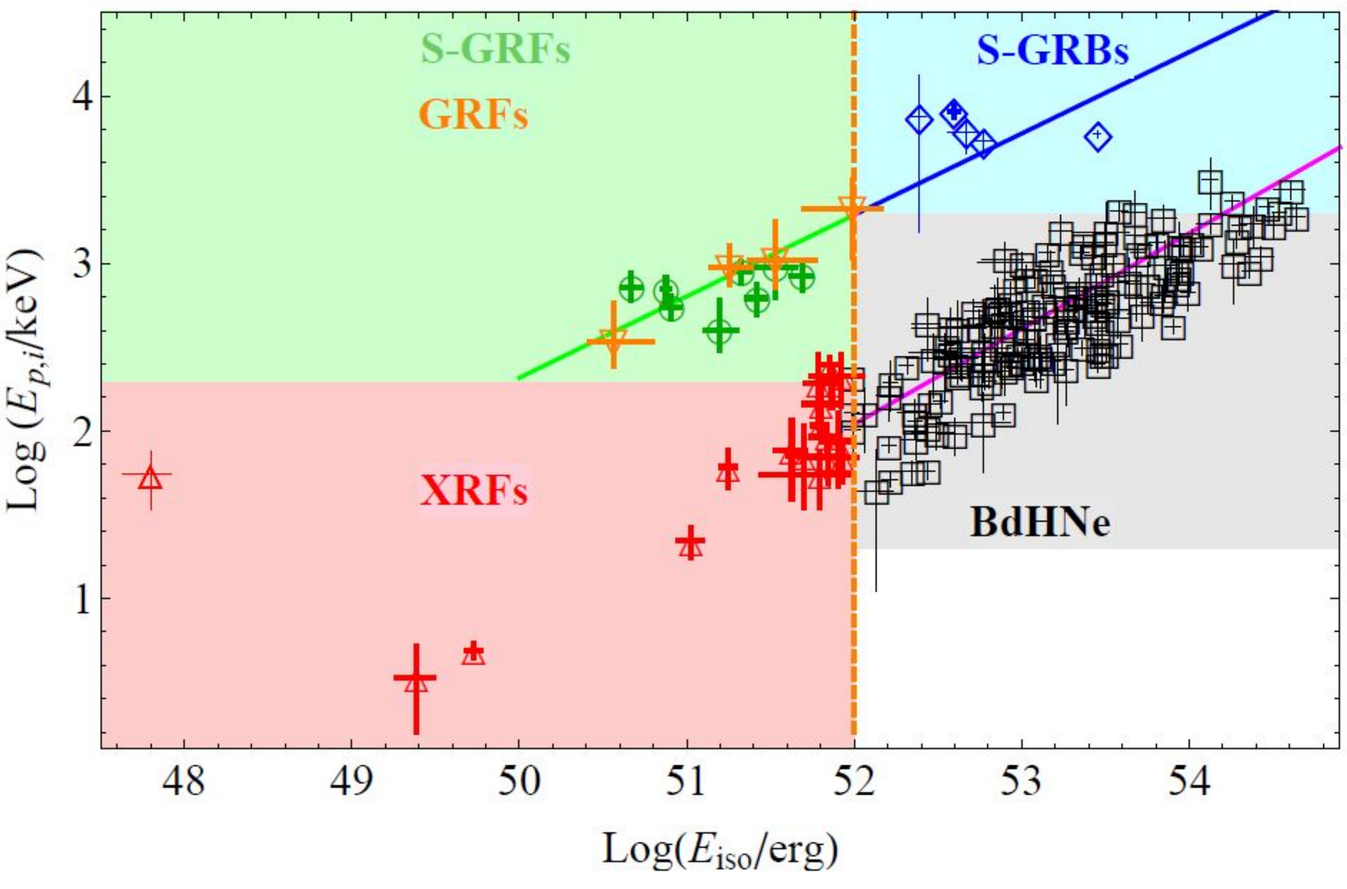




Lusso et al. 2019

Amati relation: GRB classes and progenitors

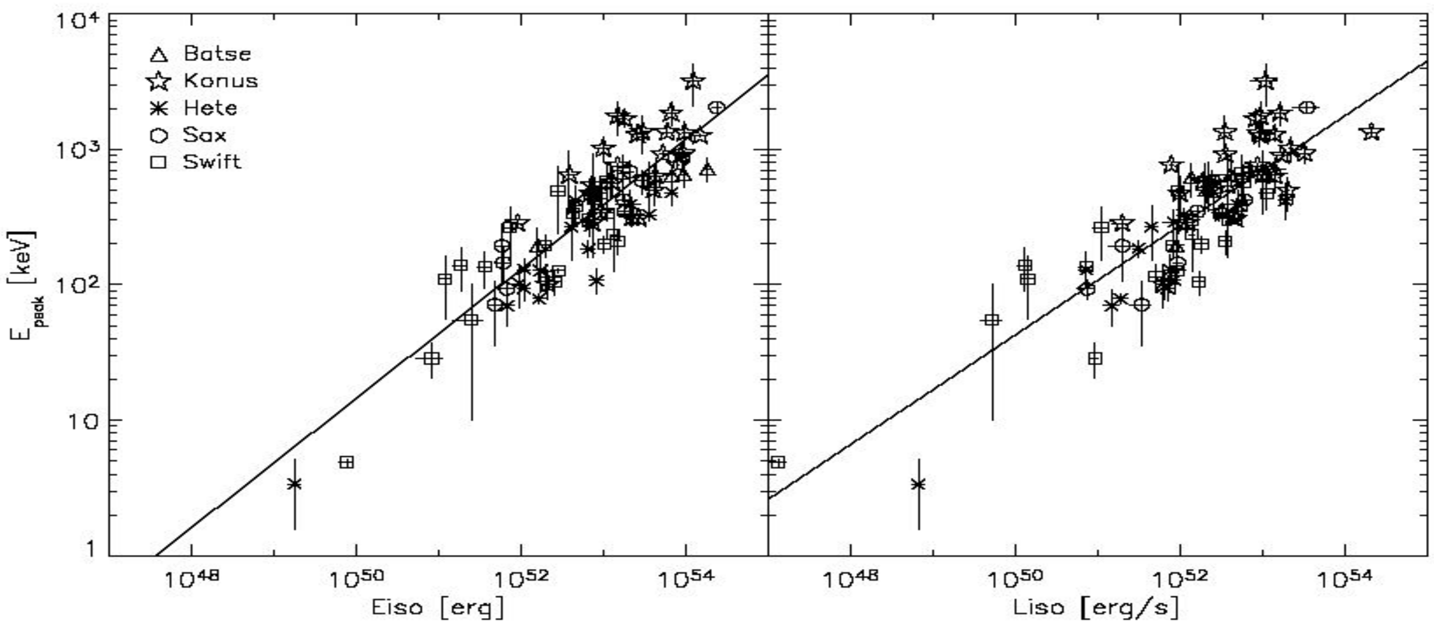
- The Ep,i – Eiso plane and correlation is fundamental for identifying and understanding the origin and physics of different GRB classes



Ruffini et al. 2016

Correlation of Ep,i with other "intensity" indicators

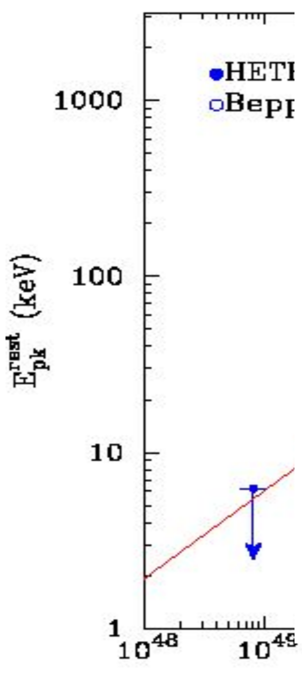
- the correlation holds also when substituting Eiso with Liso (e.g., Lamb et al. 2004) or Lpeak,iso (Yonetoku et al. 2004, Ghirlanda et al., 2005)
- this is expected because **Liso and Lpeak,iso are strongly correlated with Eiso**
- w/r to Eiso, **Lp,iso is subject to more uncertainties** (e.g., light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



Nava et al. 2009

Correlation of Ep,i with other "intensity" indicators

- the correlation … b et al. 2004) or Lpeak,iso (Yon…
- this is expecte… **ed with Eiso**
- w/r to Eiso, **Lp**… es peak at different times in differe… estimate; which peak time scale…



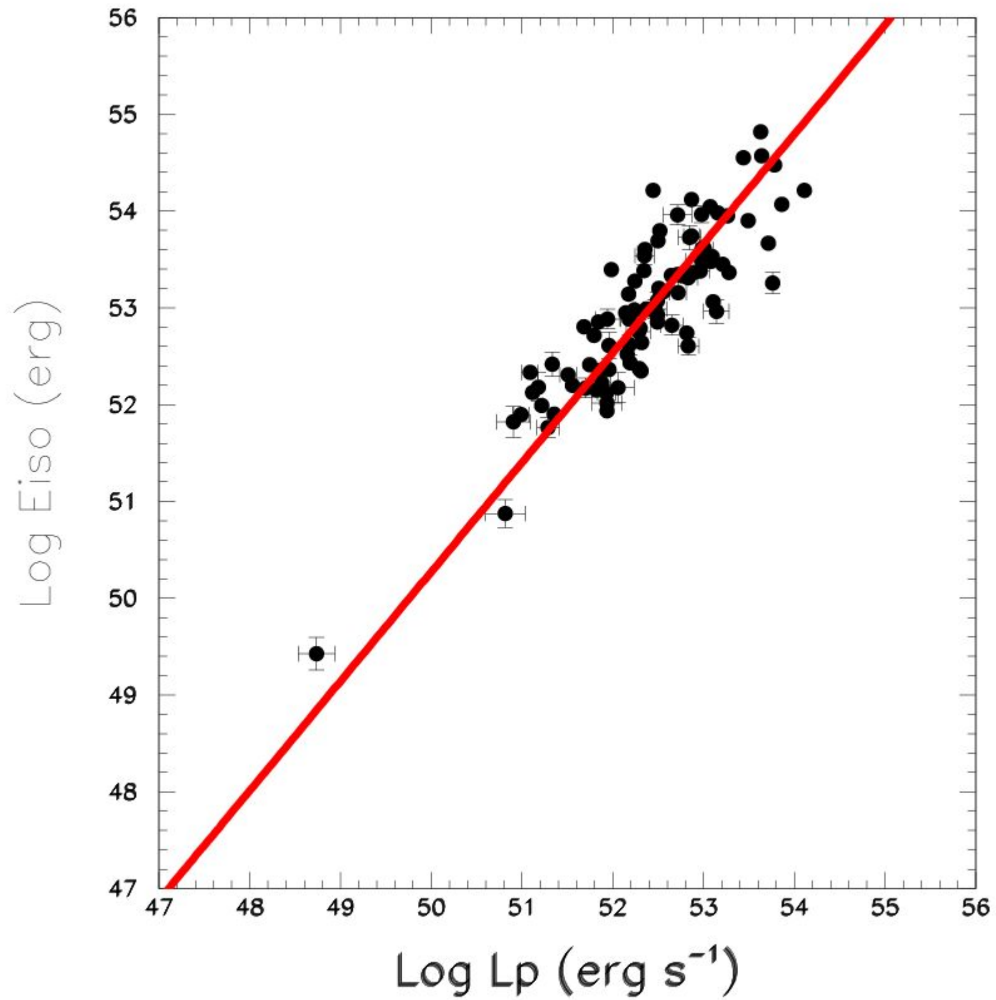
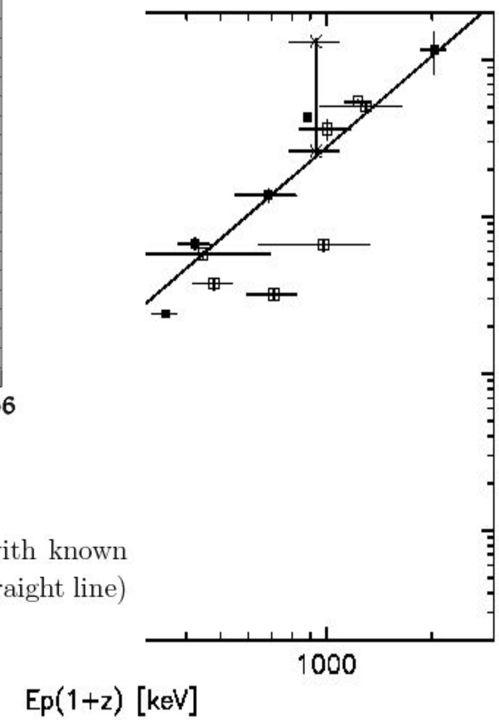
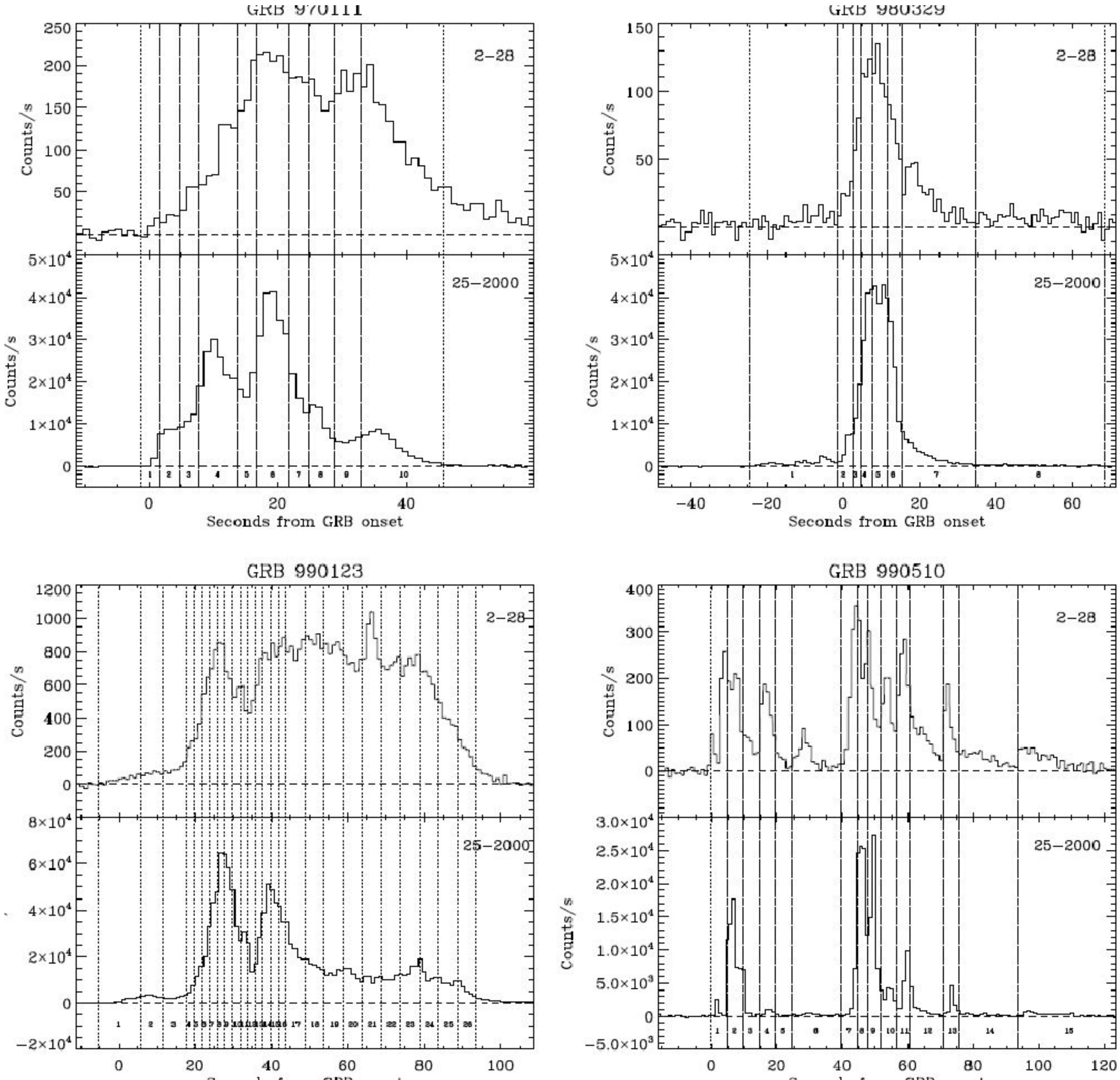


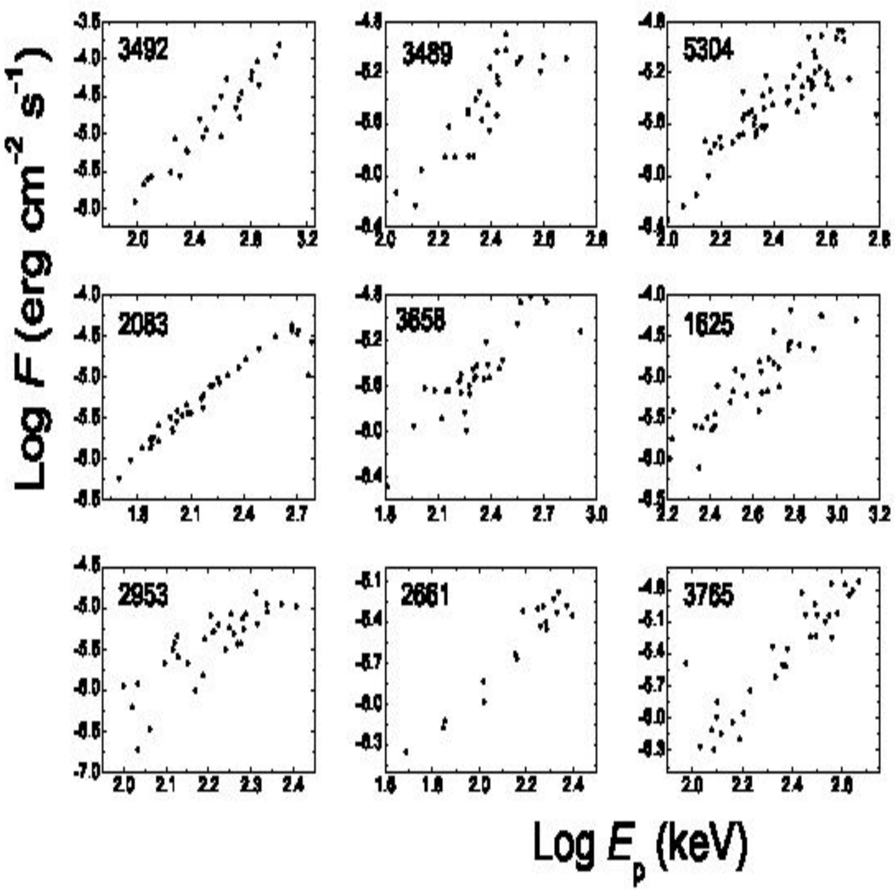
Fig. 3.— The observed correlation between $E_{\gamma,iso}$ and $L_{p,\gamma}$ and for 96 GRBs with known redshift compiled by Yonetoku et al. (2010) The best fit power-law correlation (straight line) has a power-law index 1.13 .



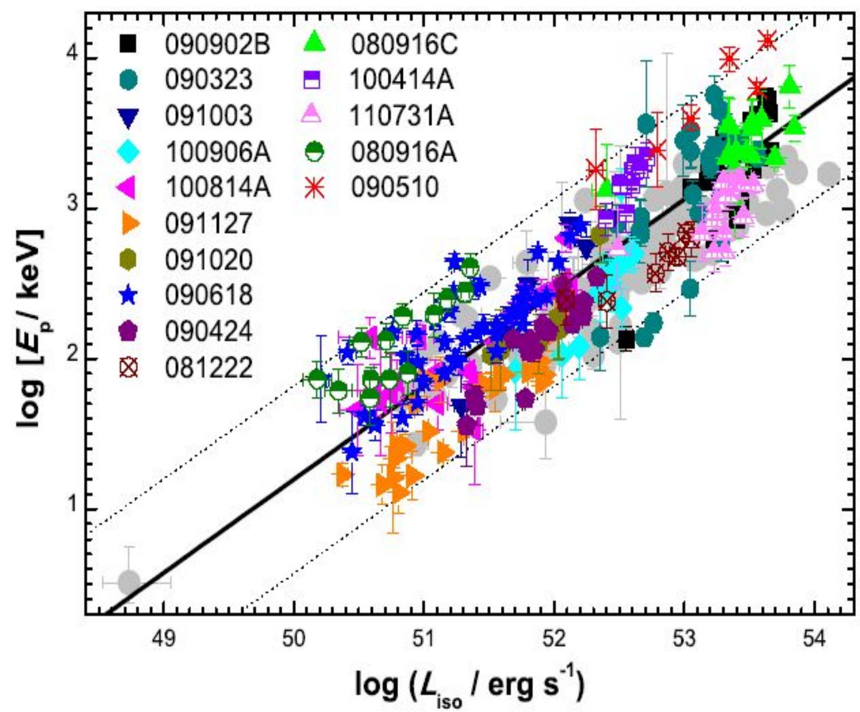


GRB 970111
GRB 980329
GRB 990123
GRB 990510
2-28
25-2000
Counts/s
Seconds from GRB onset

 the Ep,i– Liso and Ep,i – Eiso correlation holds also within a good fraction of GRBs (Liang et al.2004, Firmani et al. 2008, Ghirlanda et al. 2009, Li et al. 2012, Frontera et al. 2012, Basak et al. 2013): **robust evidence for a physical origin and clues to explanation**



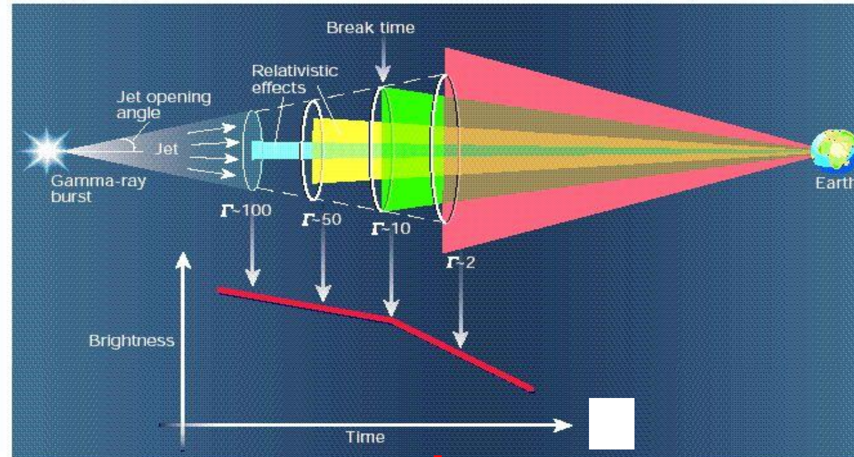
BATSE (Liang et al., ApJ, 2004)



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

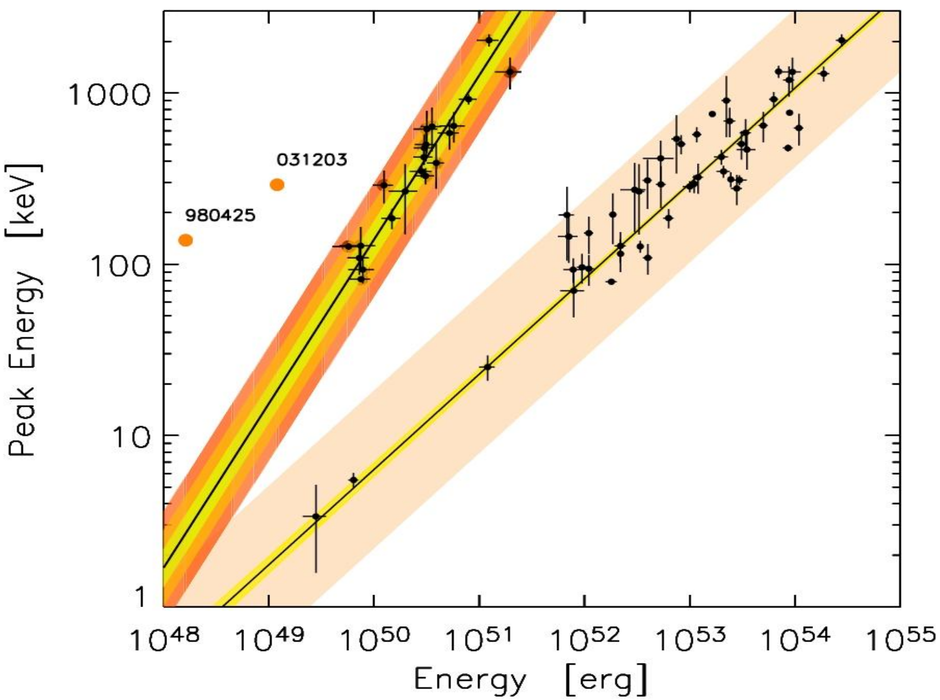
❑ Accounting for collimation

- 2004: evidence that by substituting Eiso with the collimation corrected energy Eγ the logarithmic dispersion of the correlation decreases significantly and is low enough to allow its use to standardize GRB (Ghirlanda et al., Dai et al, and many)



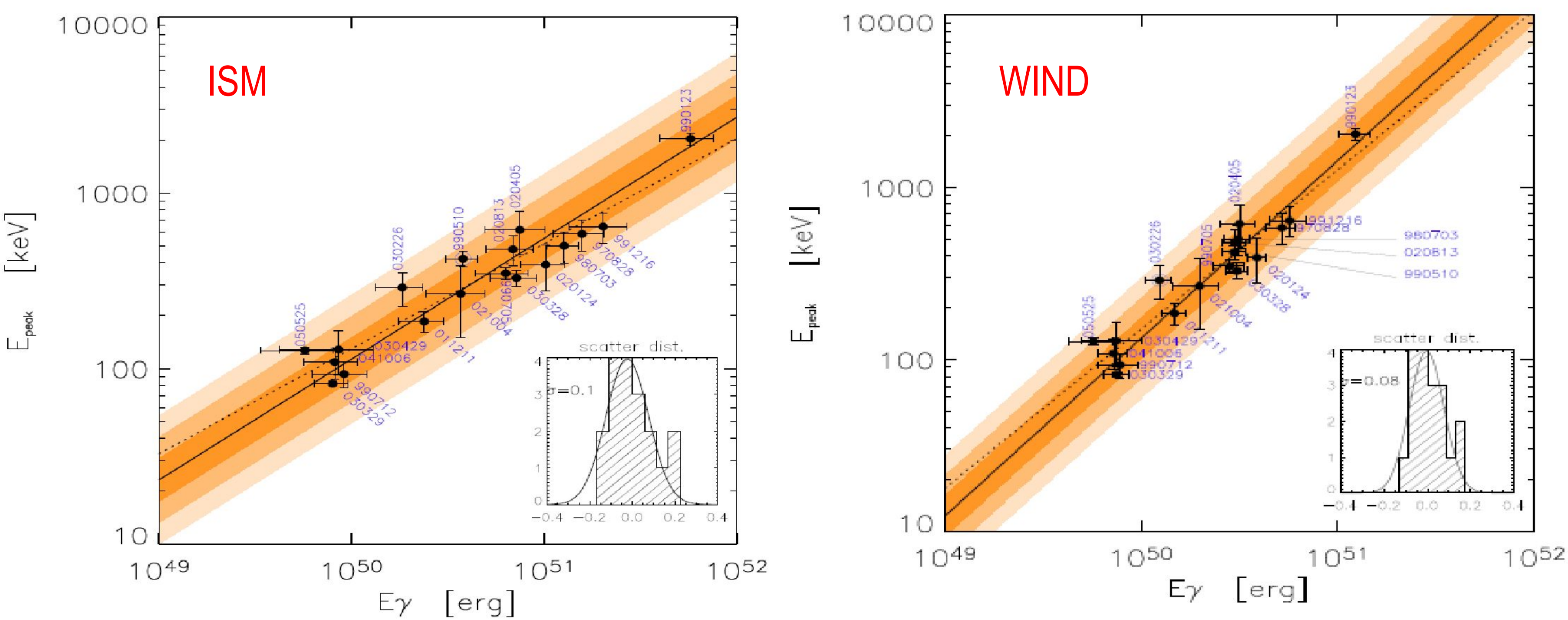
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

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



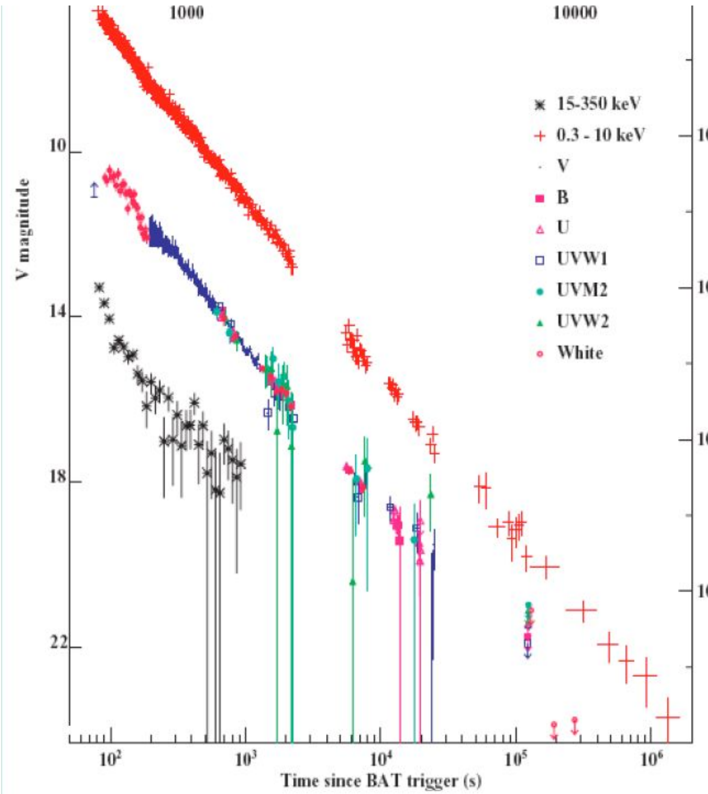
Accounting for collimation: drawbacks

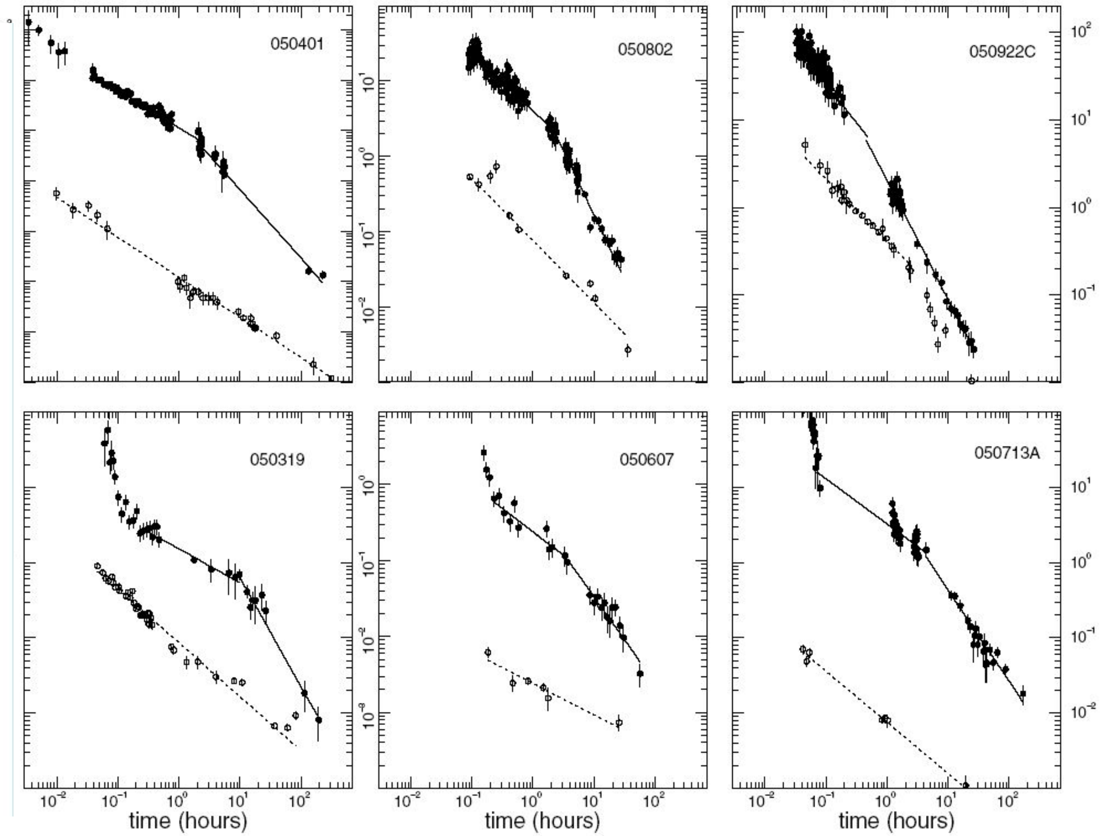
- the Ep-Eγ correlation **is model dependent**: slope depends on the assumptions on the circum-burst environment density profile (ISM or wind)
- **addition of a third observable introduces further uncertainties** (difficulties in measuring t_break, chromatic breaks, model assumptions) and substantially reduces the number of GRB that can be used (e.g., #Ep,i – Eγ ~ ¼ #Ep,i – Eiso)



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

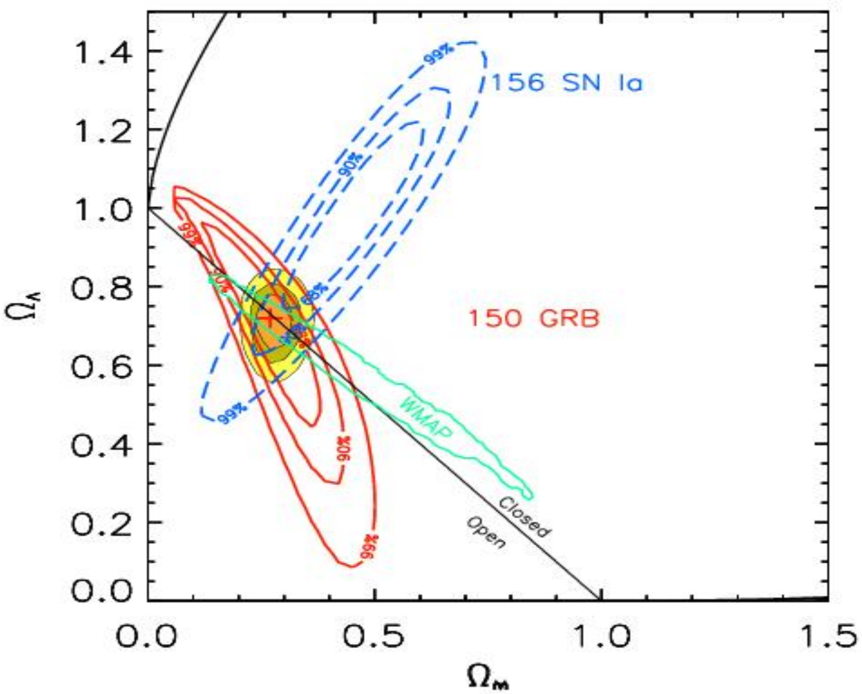
- lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break
- challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory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

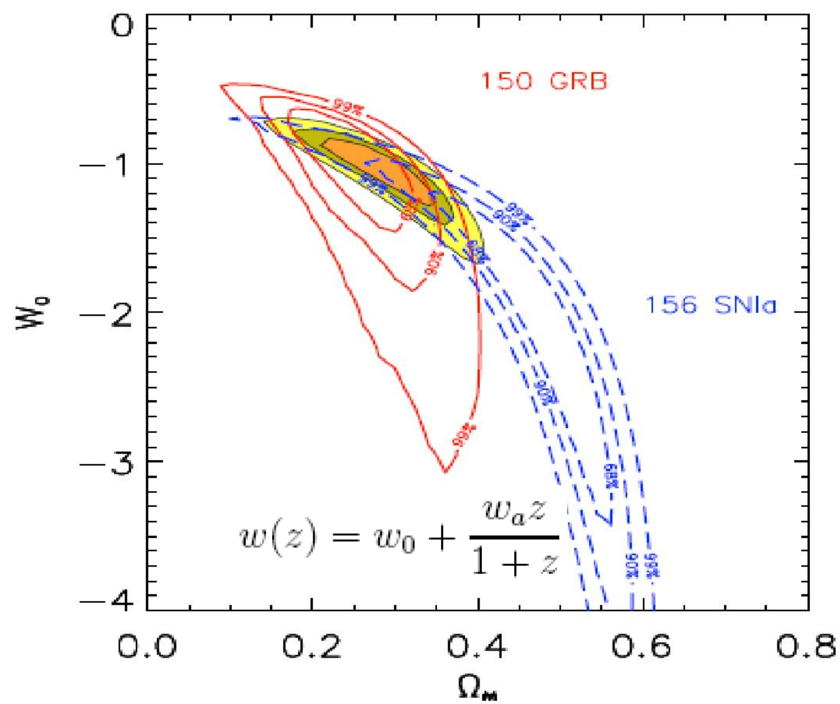




Accounting for collimation: perspectives

- the simulatenous operation of Swift, Fermi/GBM, Konus-WIND is allowing an increase of the useful sample (z + Ep) at a rate of 20 GRB/year, providing an increasing accuracy in the estimate of cosmological parameters
- future GRB experiments (e.g., SVOM) and 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)





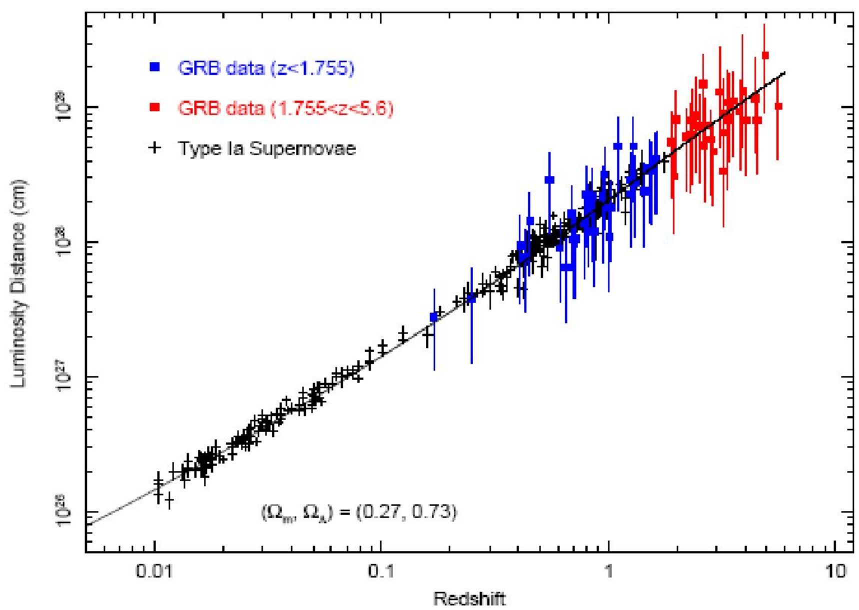
Adapted from Ghirlanda+ 2007

Calibrating the Ep,i – Eiso correlation with SN Ia

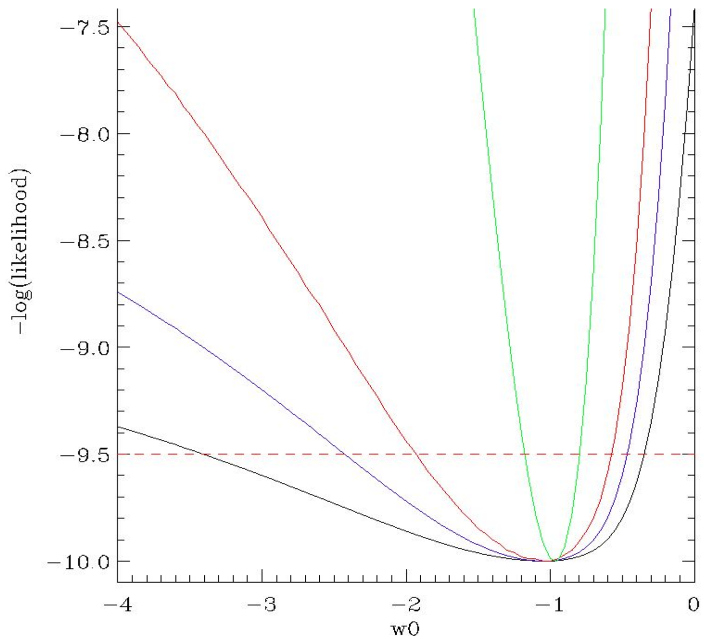
- Several authors (e.g., Kodama et al., 2008; Liang et al., 2008, Li et al. 2008, Demianski et al. 2010-2011, Capozziello et al. 2010, Wang et al. 2012) are investigating the calibration of the Ep,i - Eiso correlation at z < 1.7 by using the luminosity distance – redshift relation derived for SN Ia

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

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



Kodama et al. 2008

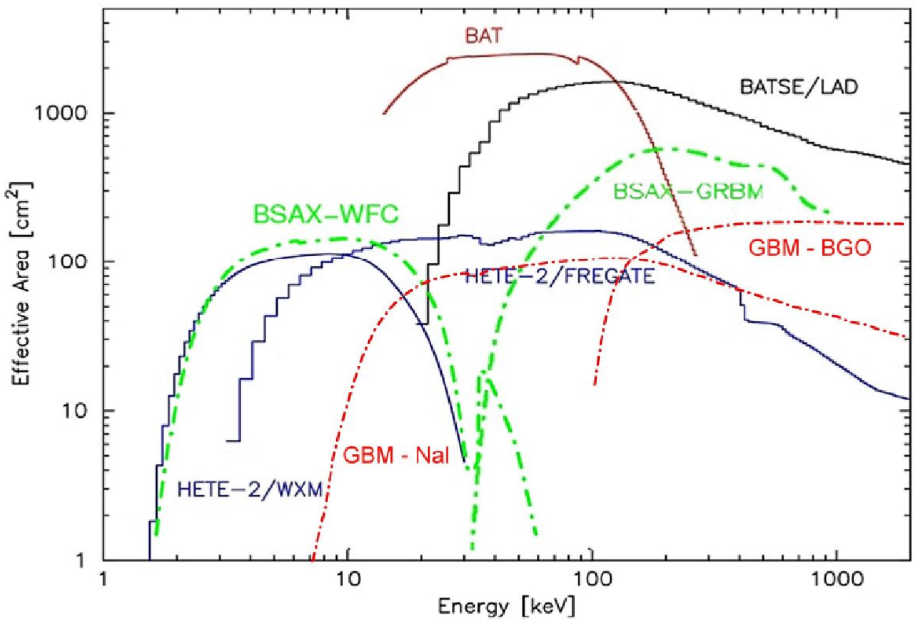


Amati & Della Valle 13, Amati+ 13

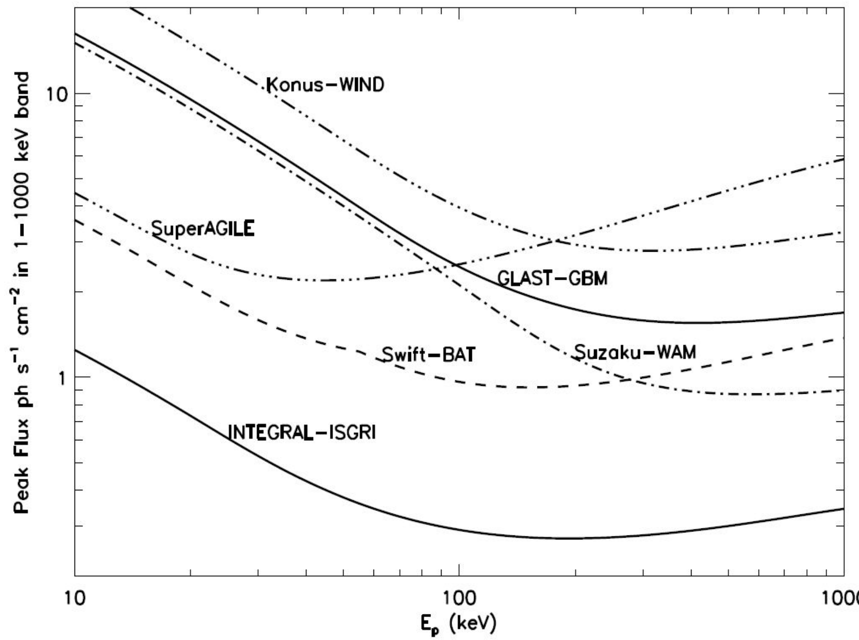
But… is the Ep,i – intensity correlation real ?

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

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



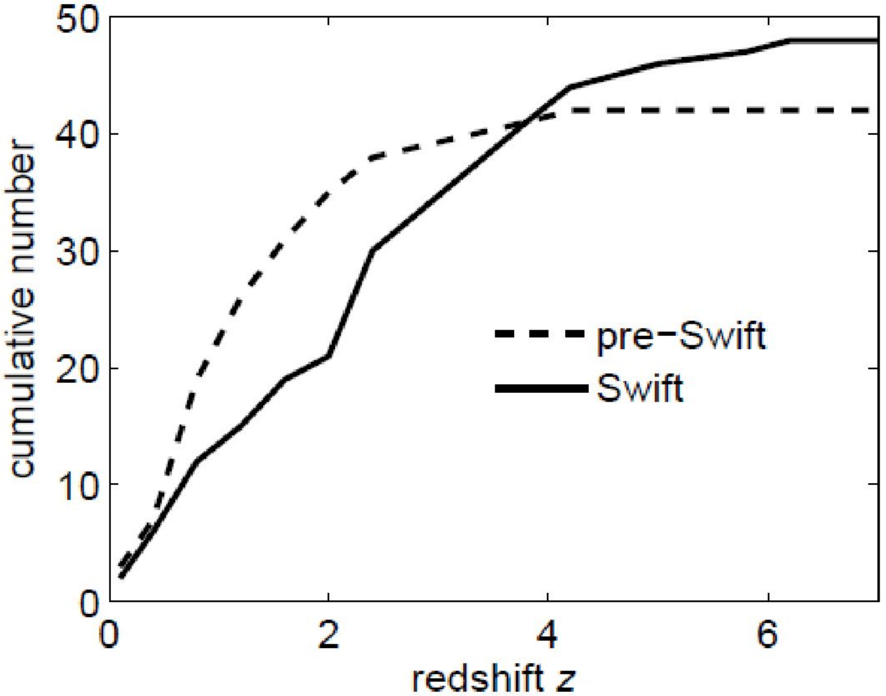
Adapted from Sakamoto et al. 2011

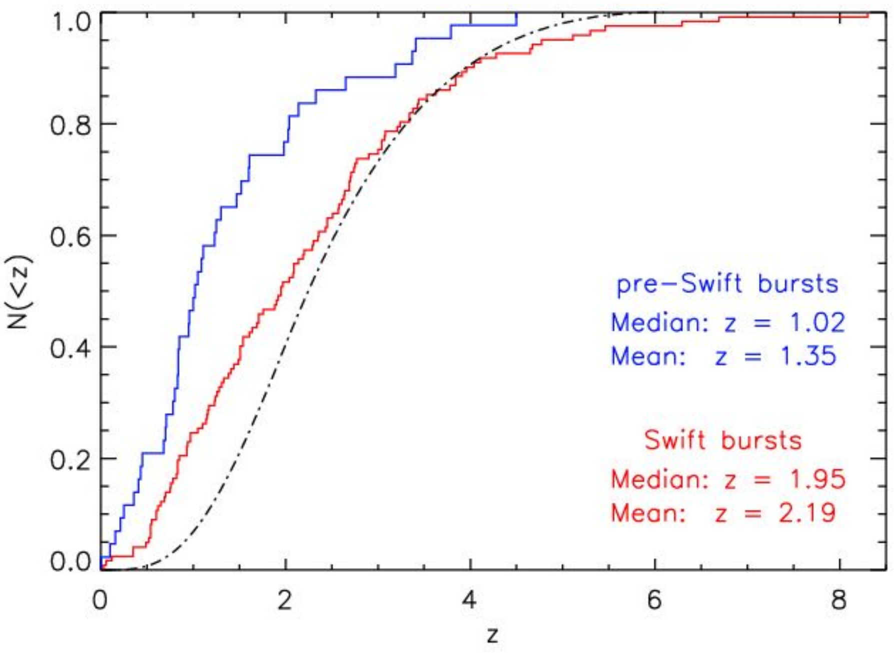


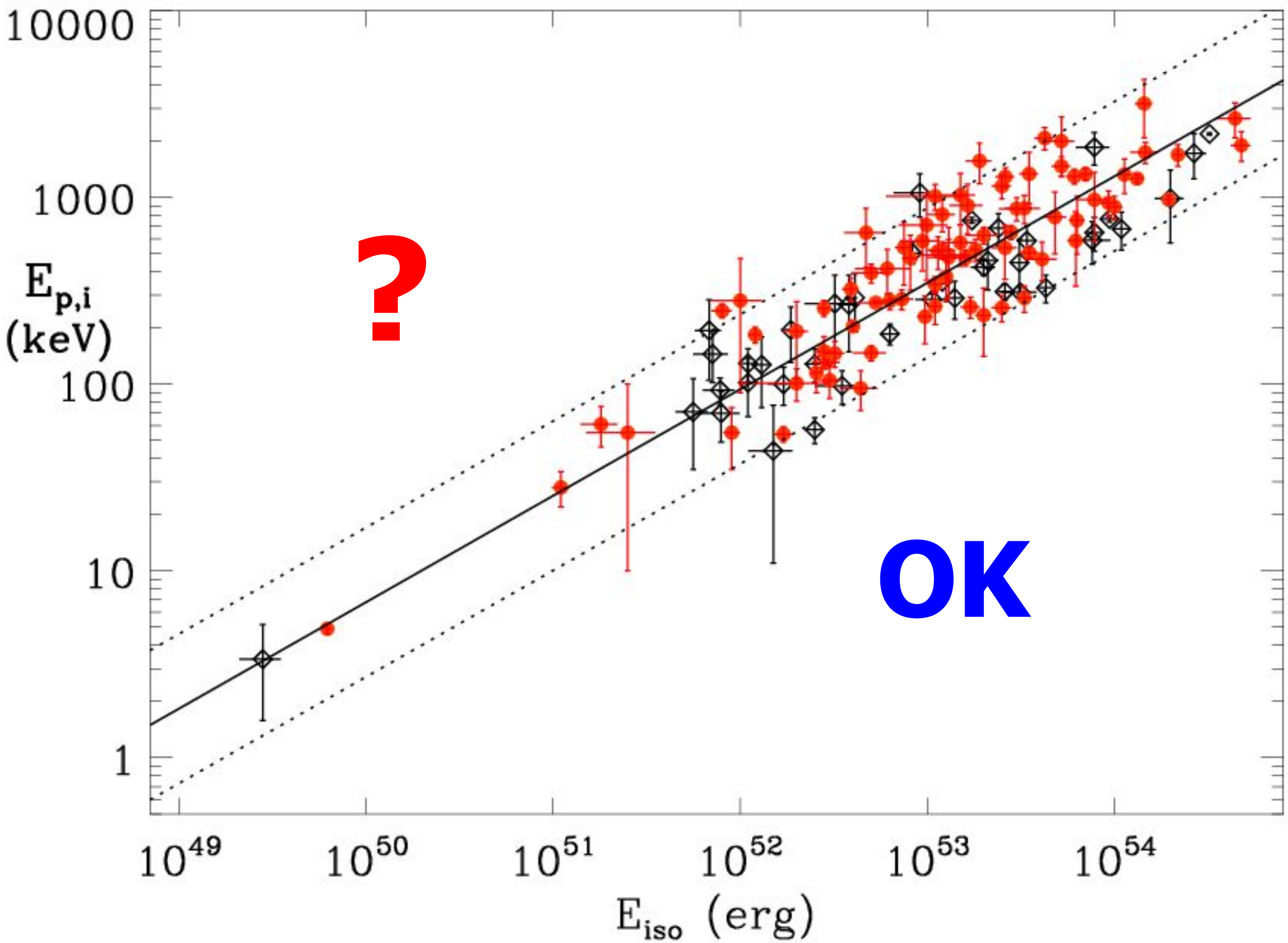
Band 2008

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

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



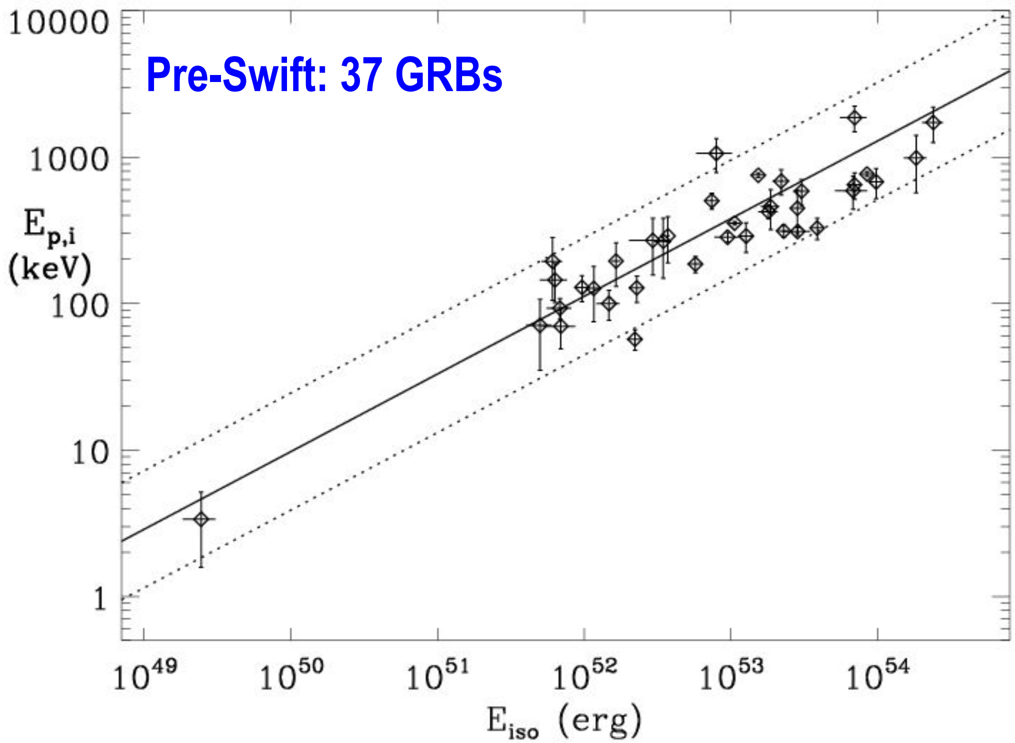



10000
1000
100
10
1
$E_{p,i}$
(keV)
?
OK
10^{49}
10^{50}
10^{51}
10^{52}
10^{53}
10^{54}
E_{iso} (erg)

GRBs WITH measured redshift

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

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



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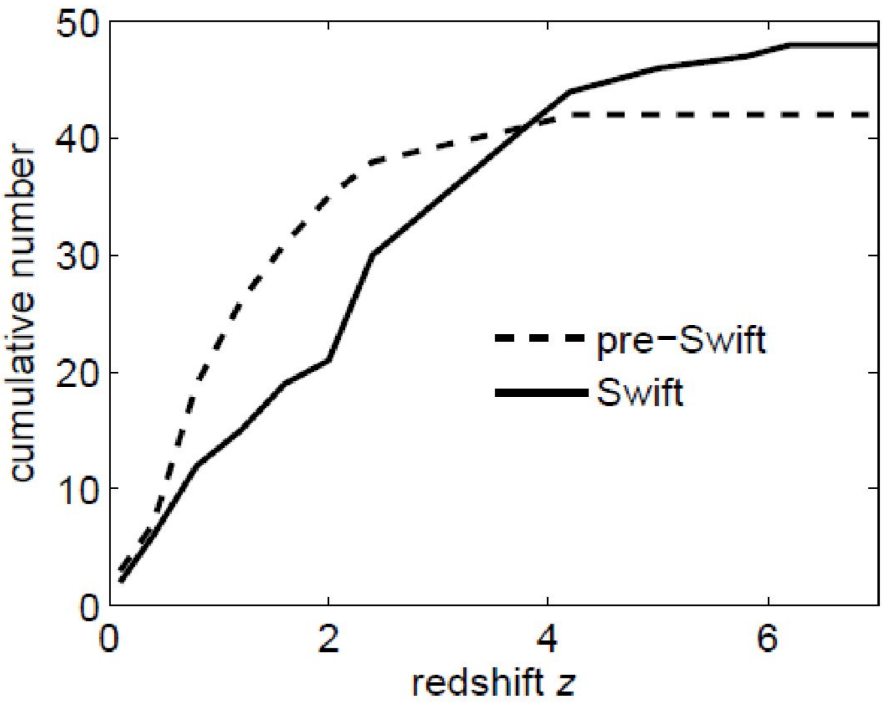
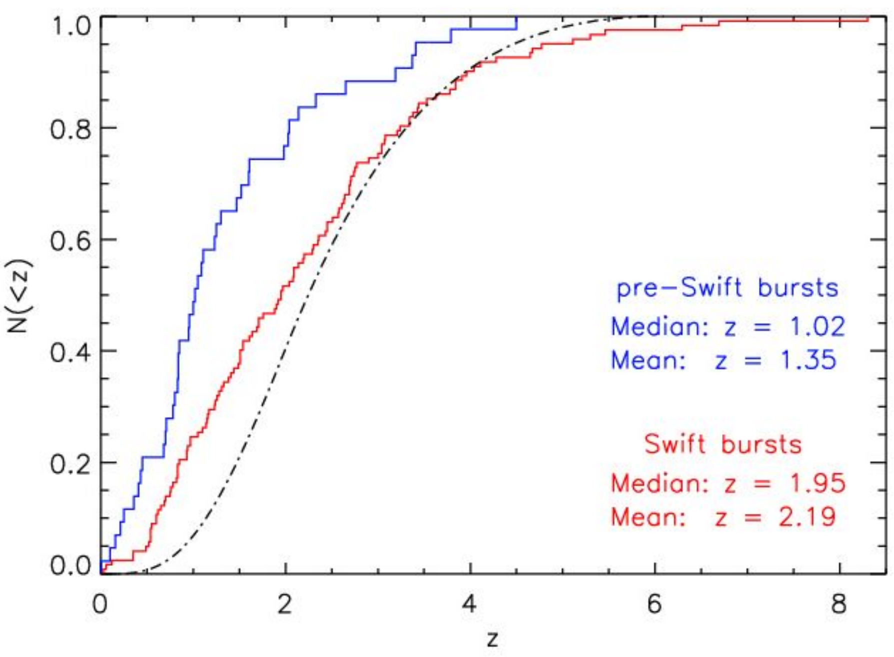
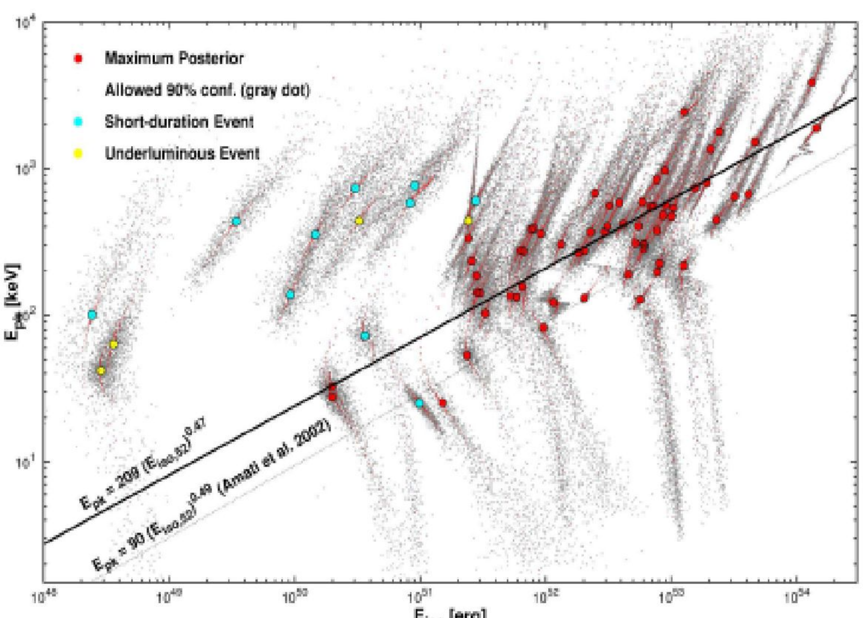


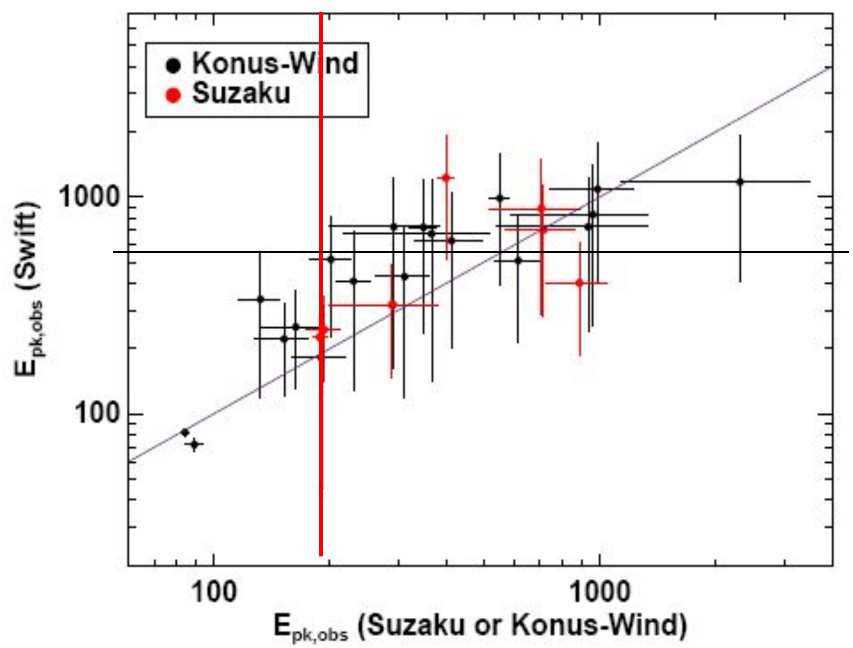


- Butler et al. based on analisys Swift/BAT spectra with a Bayesian method assuming BATSE Ep distribution: 50% of Swift GRB are inconsistent with the pre-Swift Ep,i - Eiso correlation

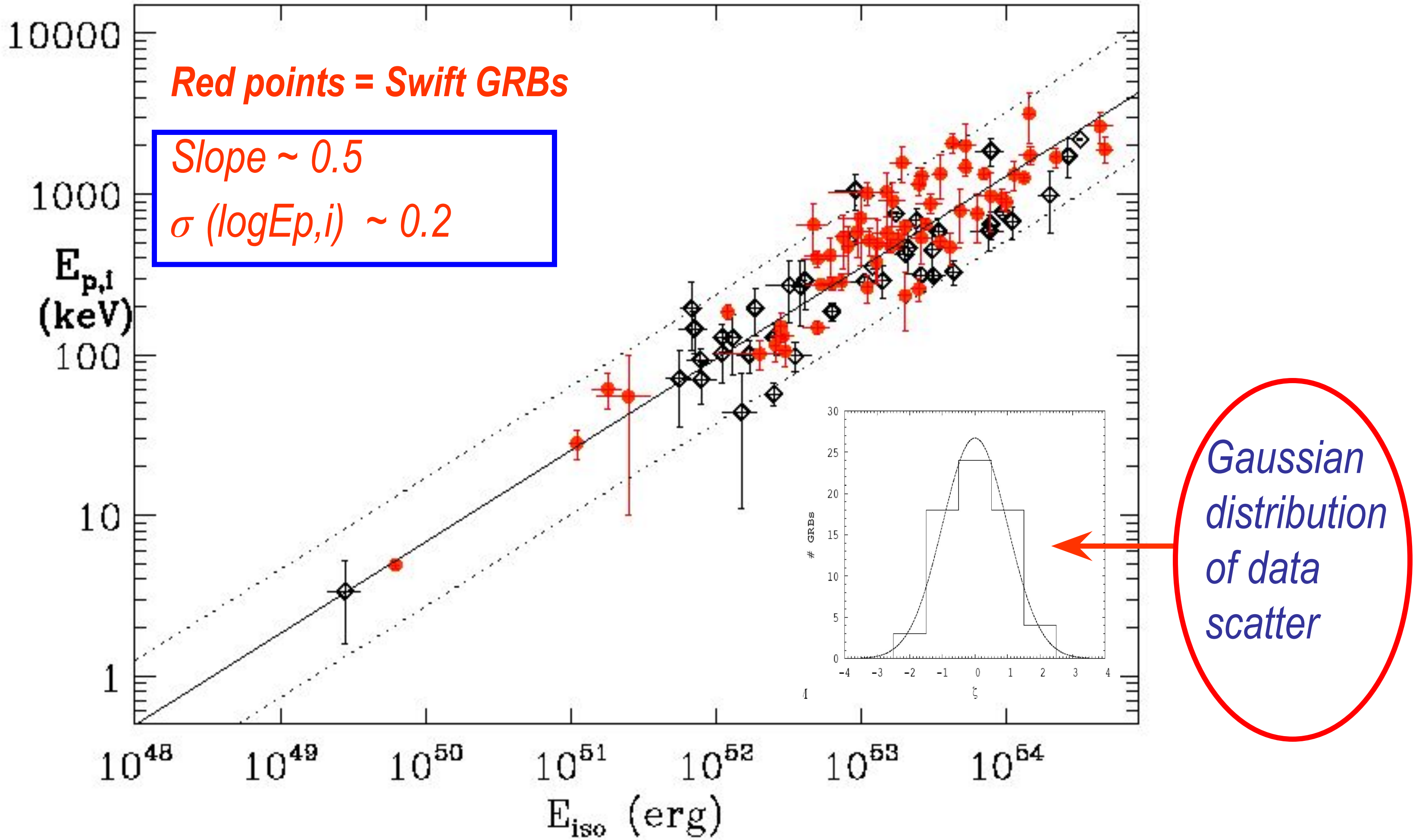
- BUT: comparison of Ep derived by them from BAT spectra using a Bayesian method and those MEASURED by Konus/Wind show that **BAT cannot measure Ep > 200 keV (as expected, given its 15-150 keV passband)**

- MOREOVER: Ep values by Butler et al. NOT confirmed by official analysis by BAT team (Sakamoto et al. 2008) and joint analysis of BAT + KW (Sakamoto et al. 2009) of BAT + Suzaku/WAM (Krimm et al. 2009) spectra.





 Ep,i of Swift GRBs **measured** by Konus-WIND, Suzaku/WAM, Fermi/GBM and BAT (only when Ep inside or close to 15-150 keV and values provided by the Swift/BAT team (GCNs or Sakamoto et al. 2008, 2011): **Swift GRBs are consistent with the Ep,i – Eiso correlation**



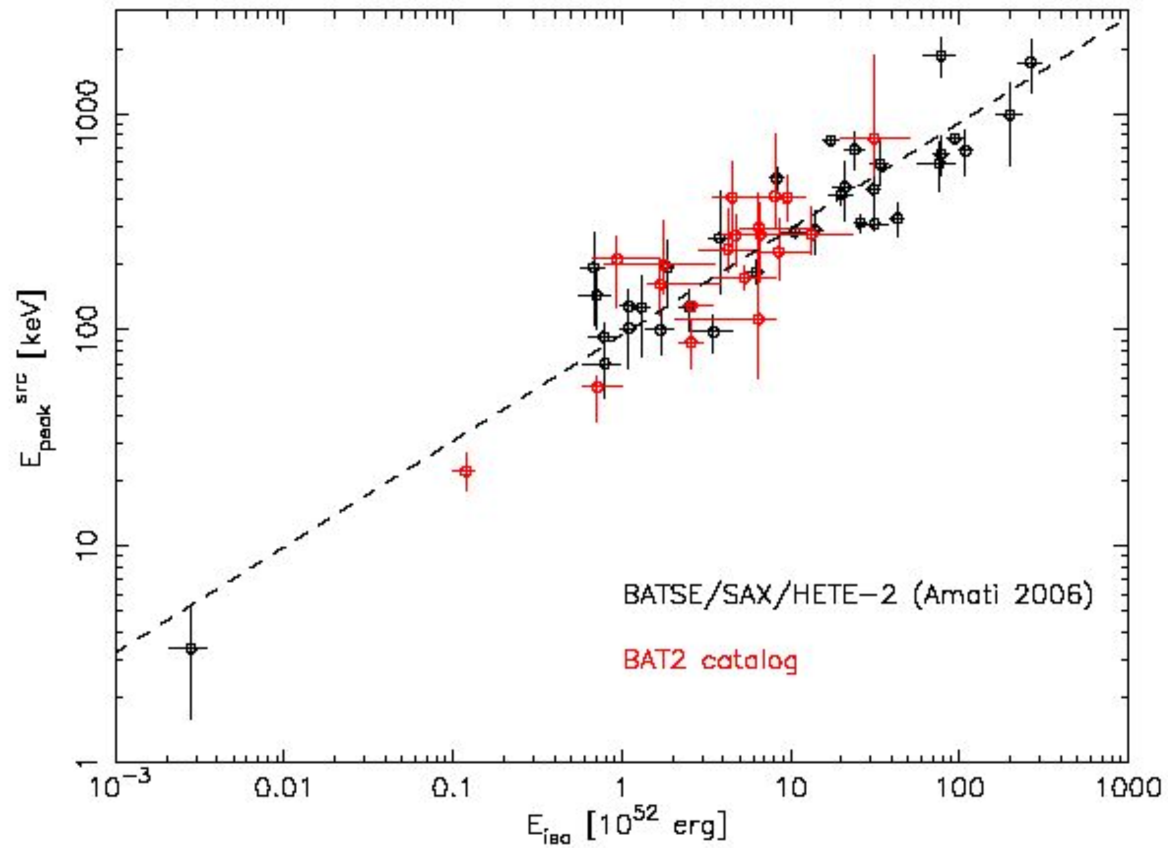
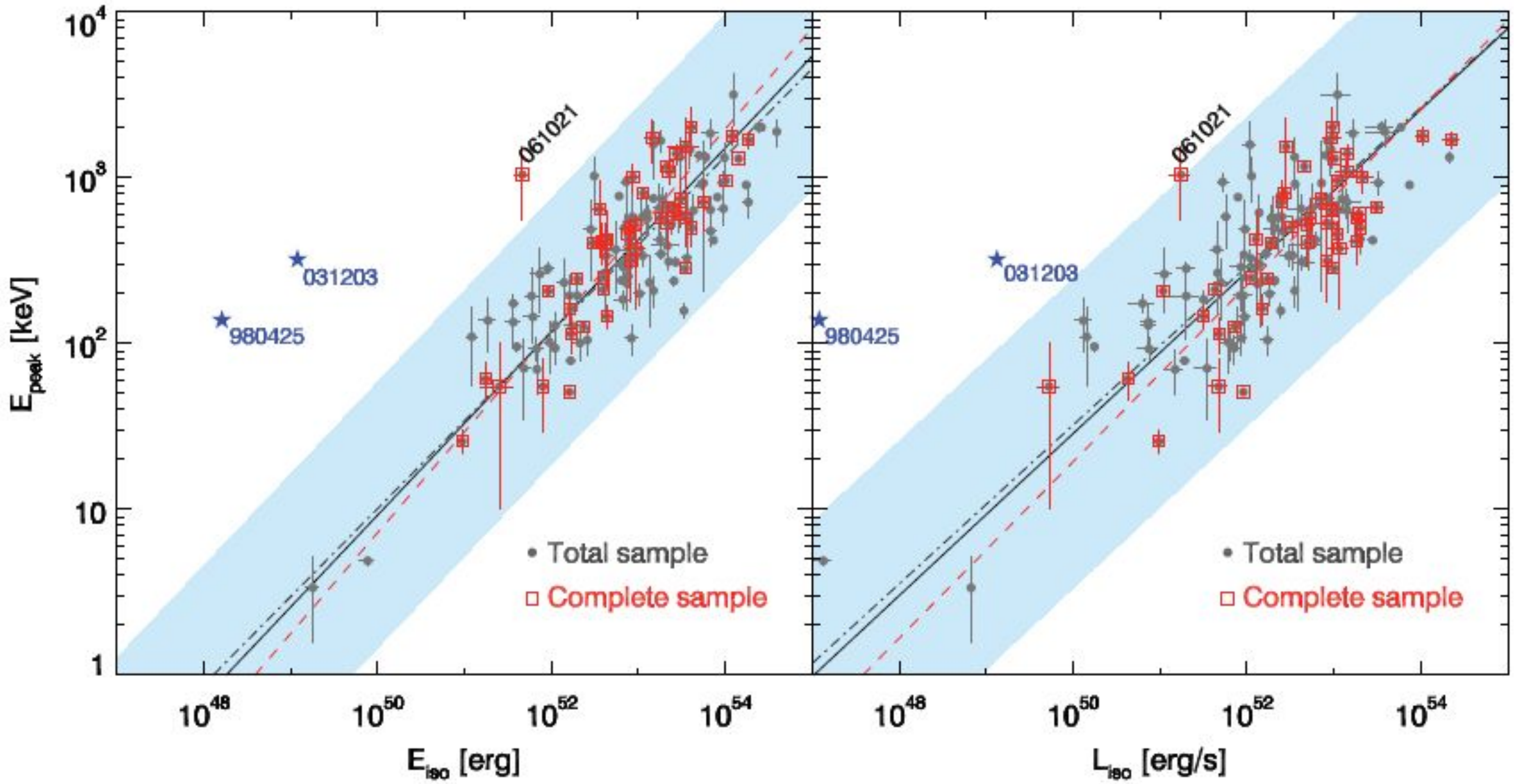


Fig. 33.— The correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ for the *Swift* GRBs (red) and other GRB missions (black). The dashed line is the best fit correlation between $E_{\rm peak}^{\rm src}$ and $E_{\rm iso}$ reported by Amati (2006): $E_{\rm peak}^{\rm src} = 95 \times (E_{\rm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

Sakamoto et al. 2011

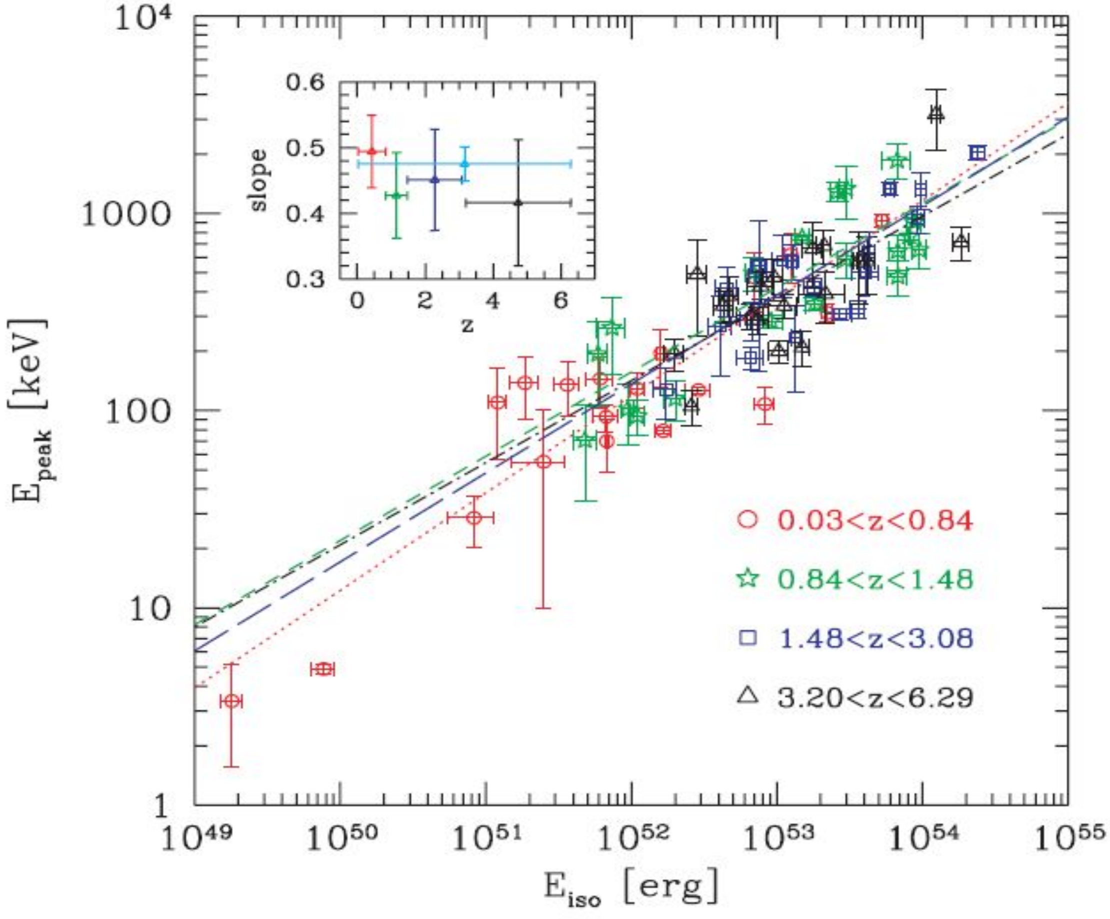
- Nava et al. 2012: Ep,i – Eiso and Ep – Lp,iso correlations confirmed by the analysis of the complete sample by Salvaterra et al. 2011 -> further evidence of low impact of selection effects in redshift

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



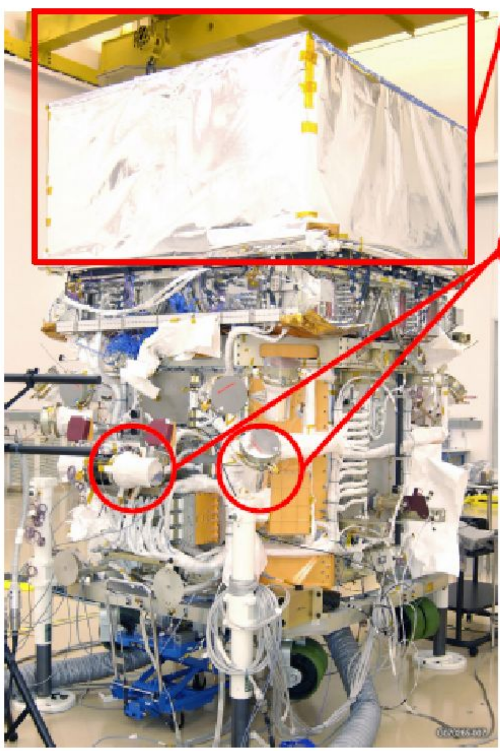
Nava et al. 2012, "complete sample of Salvaterra et al. 2011"

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

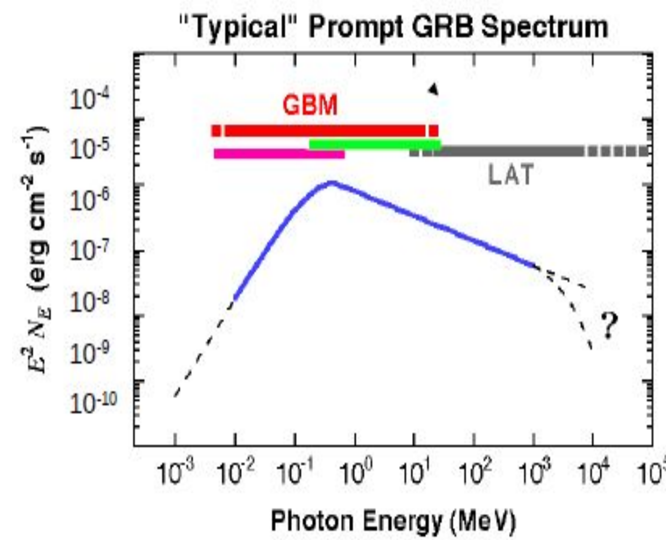


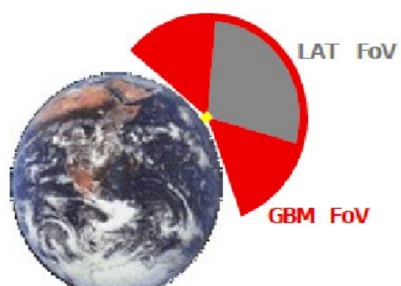
Ghirlanda et al. 2008

- ❑ Detection, arcmin localization and **study of GRBs in the GeV energy range** through the ***Fermi*/LAT instrument**, with dramatic improvement w/r CGRO/EGRET
- ❑ Detection, rough localization (a few degrees) and **accurate determination of the shape of the spectral continuum of the prompt emission of GRBs from 8 keV up to 30 MeV through the Fermi/GBM instrument**



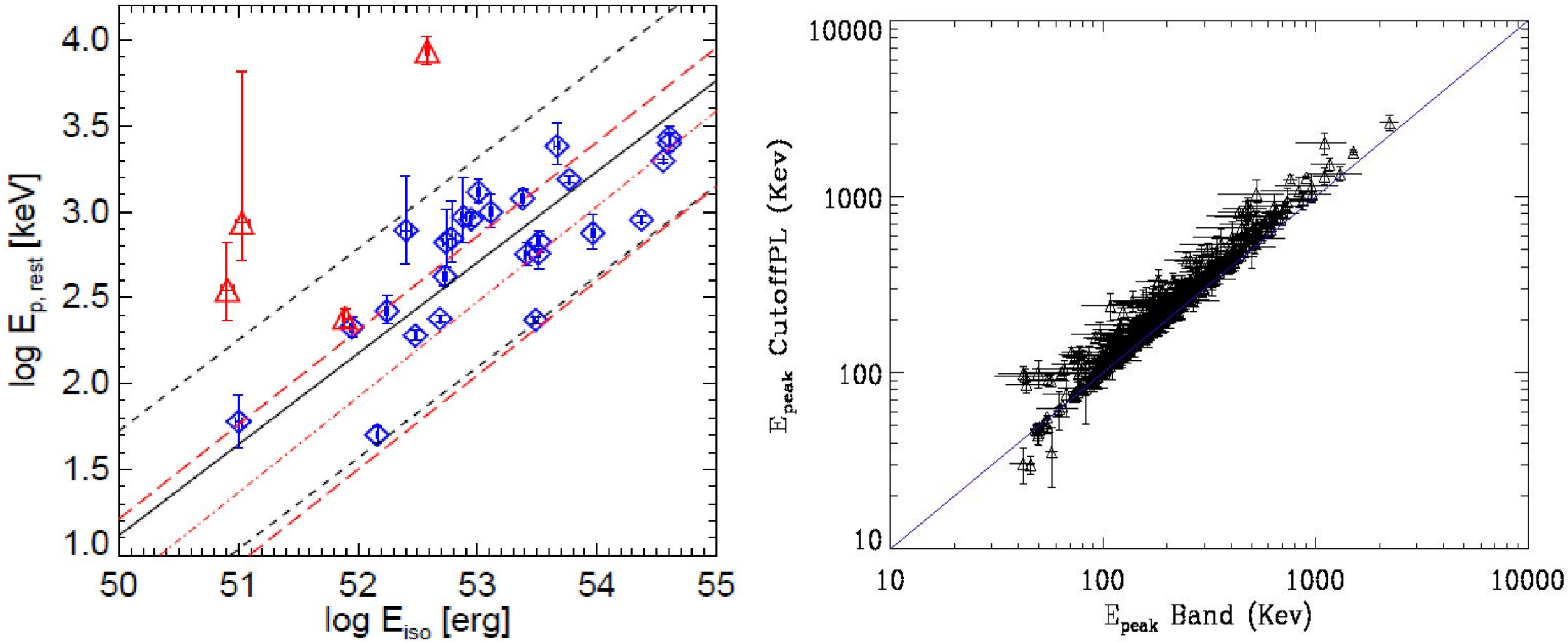
- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.





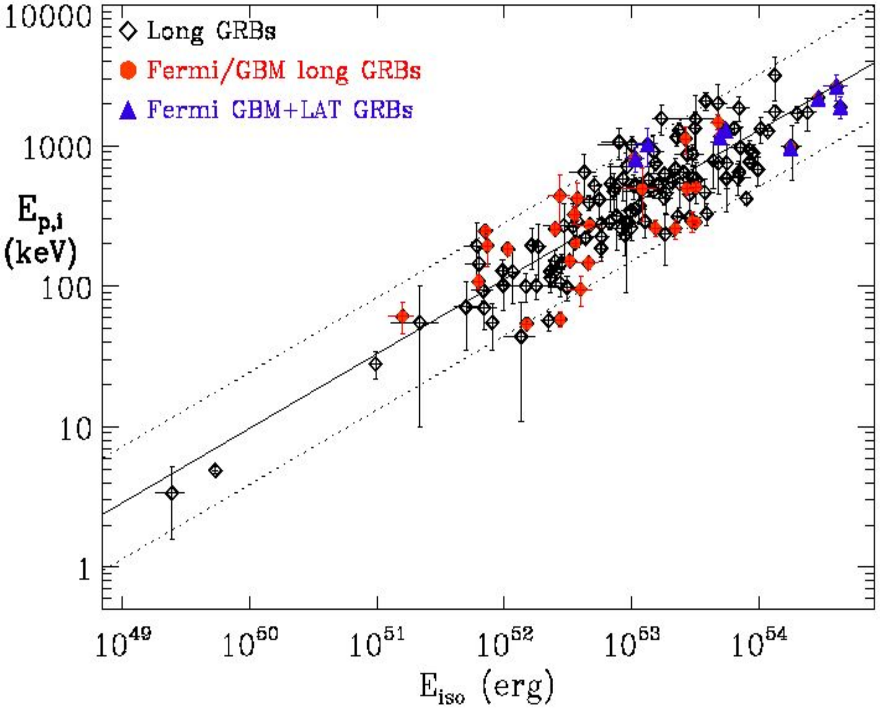
- *Gruber et al (2011, official Fermi team): all Fermi/*GBM long GRBs with known z are consistent with Ep,i – Eiso correlation, short GRBs are not

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

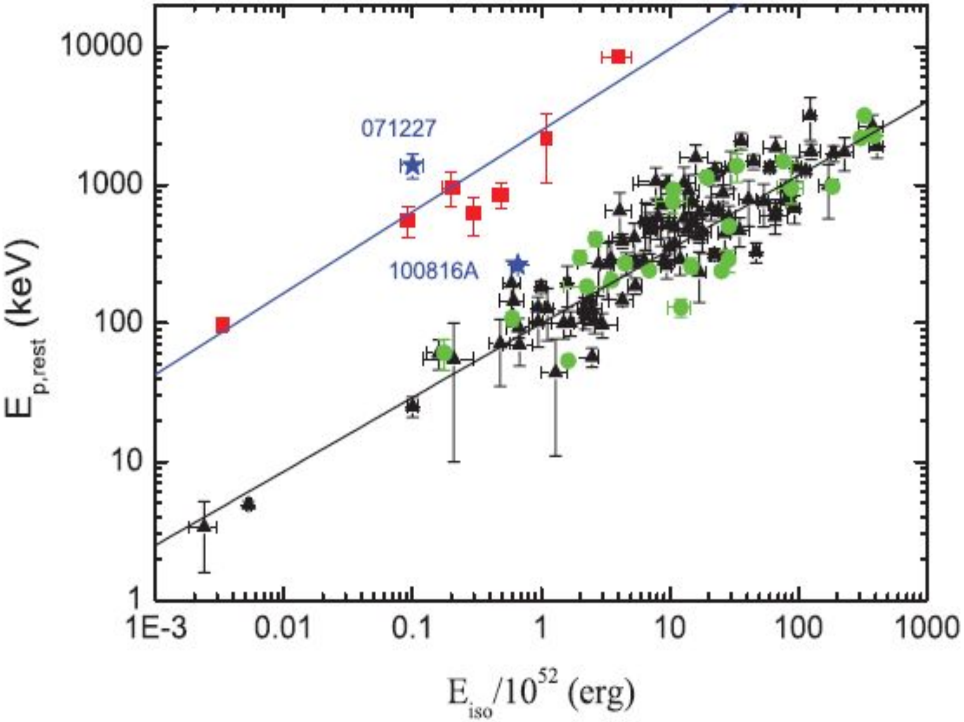


Gruber et al. 2011

- When computing Ep,i and Eiso based on the fit with Band function (unless CPL significantly better) all *Fermi/*GBM long GRBs with known z are fully consistent with Ep,i – Eiso correlation as determined with previous / other experiments, both when considering preliminary fits (GCNs) or refined analysis (e.g., Nava et al. 2011)

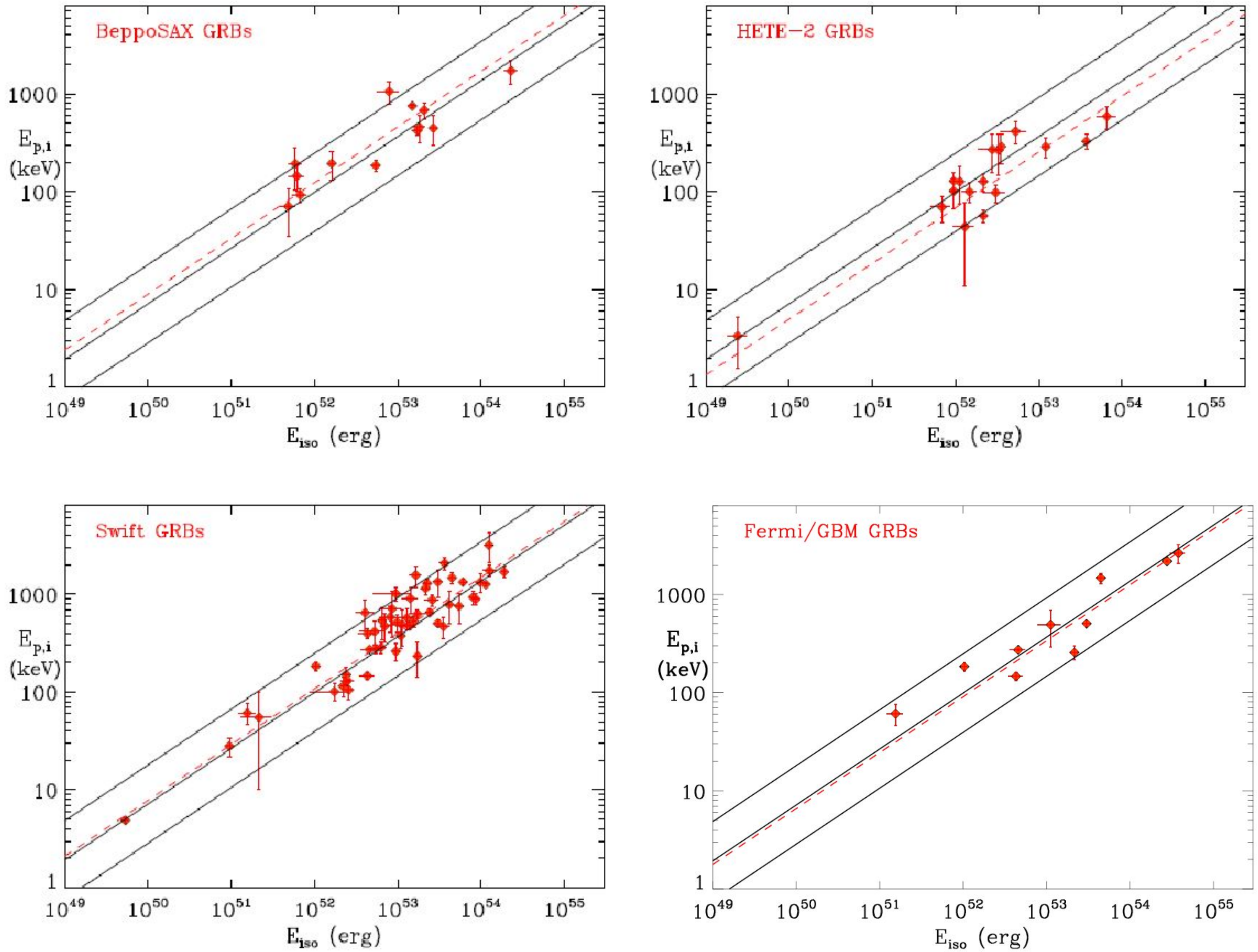


Amati 2012

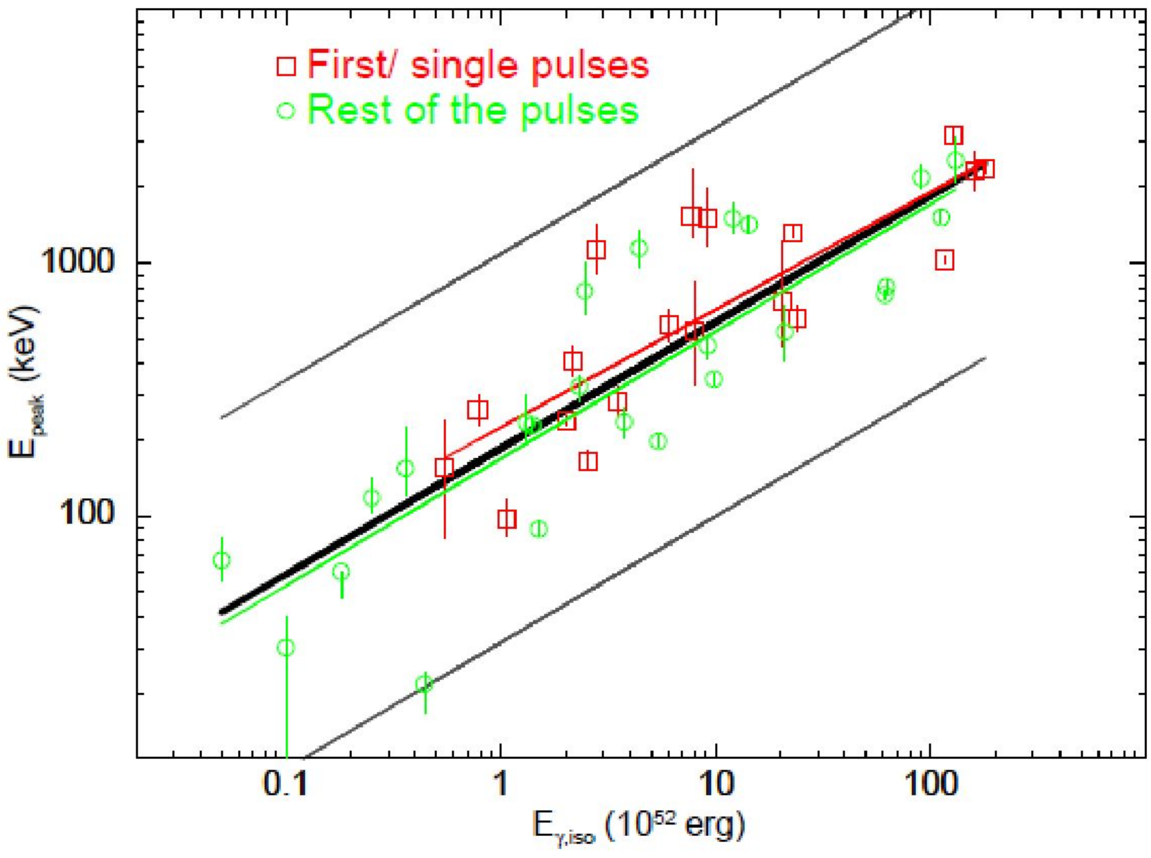


Zhang et al. 2012

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



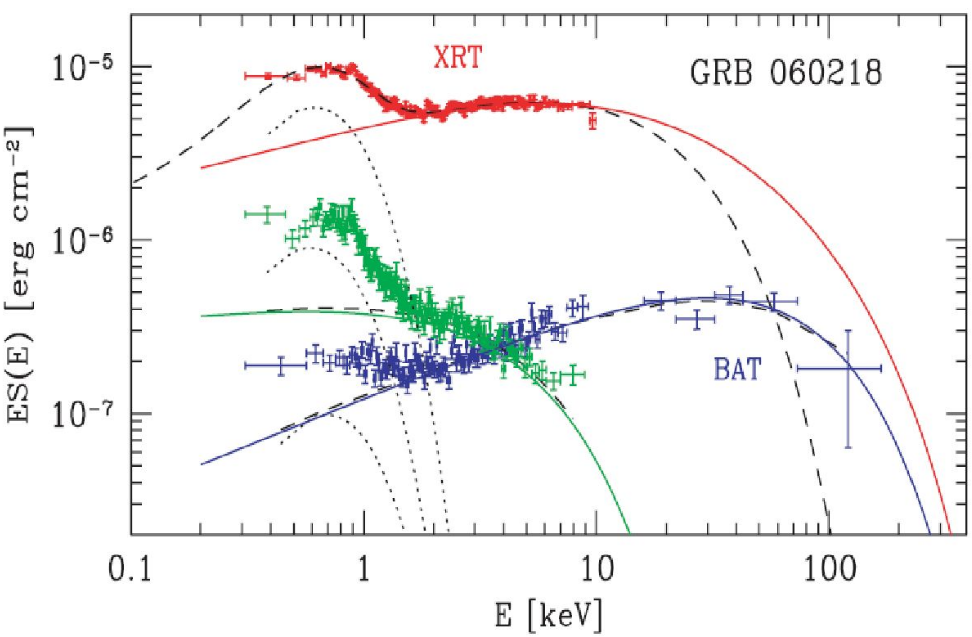
Basak et al. 2013: time-resolved Ep,i – Eiso correlation

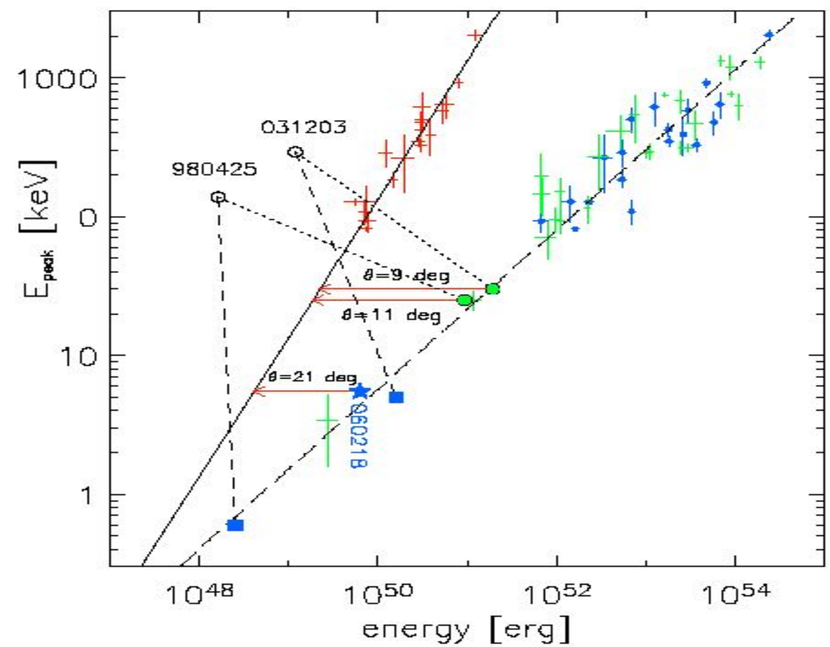


- GRB060218 was a very long event (~3000 s) and without XRT mesurement (0.3-10 keV) Ep,i would have been over-estimated and found to be inconsistent with the Ep,i-Eiso correlation

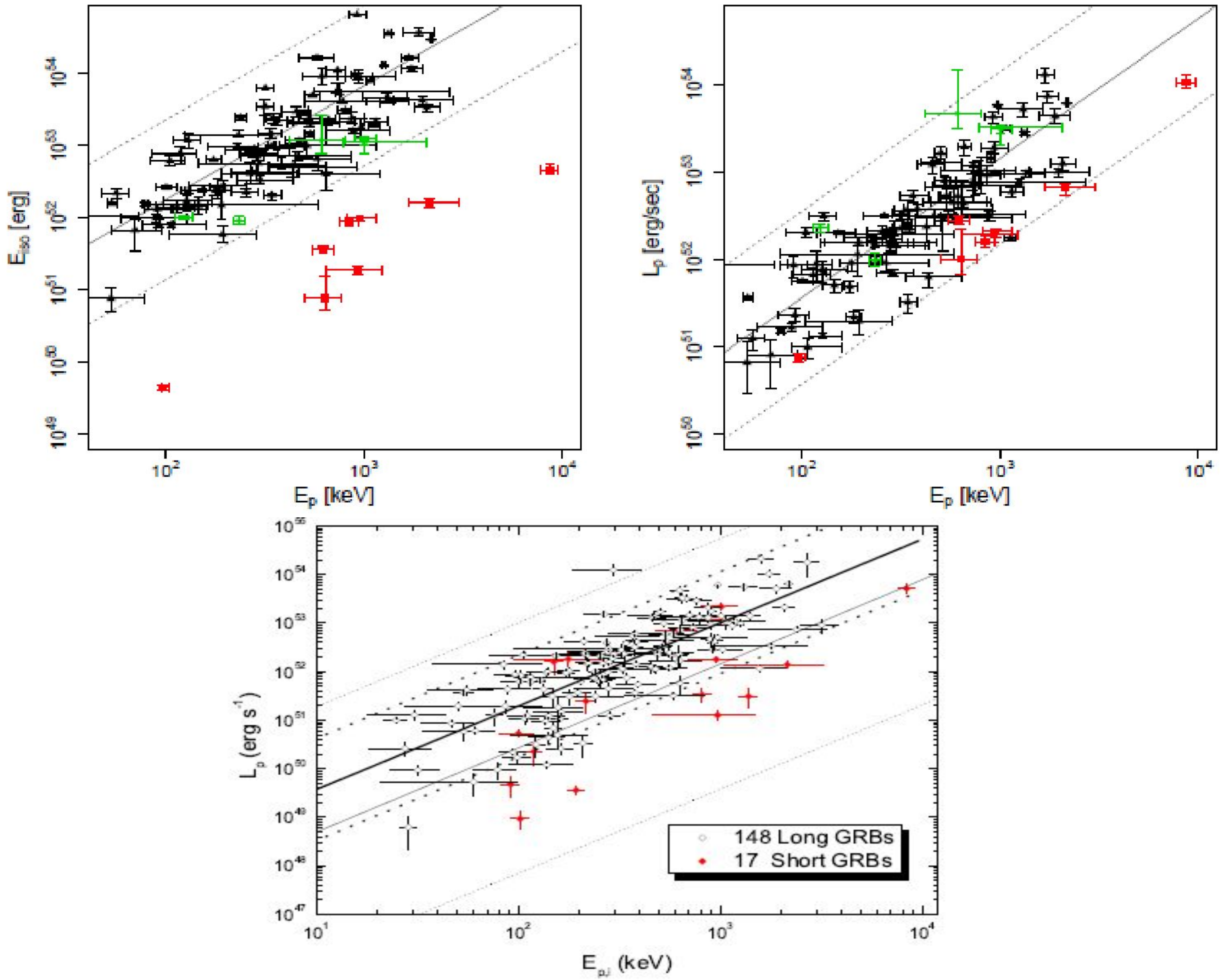
- Ghisellini et al. (2006) found that a spectral evolution model based on GRB060218 can be applied to GRB980425 and GRB031203, showing that these two events may be also consistent with the Ep,i-Eiso correlation

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





❑ 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)



GRBs WITHOUT measured redshift

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

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

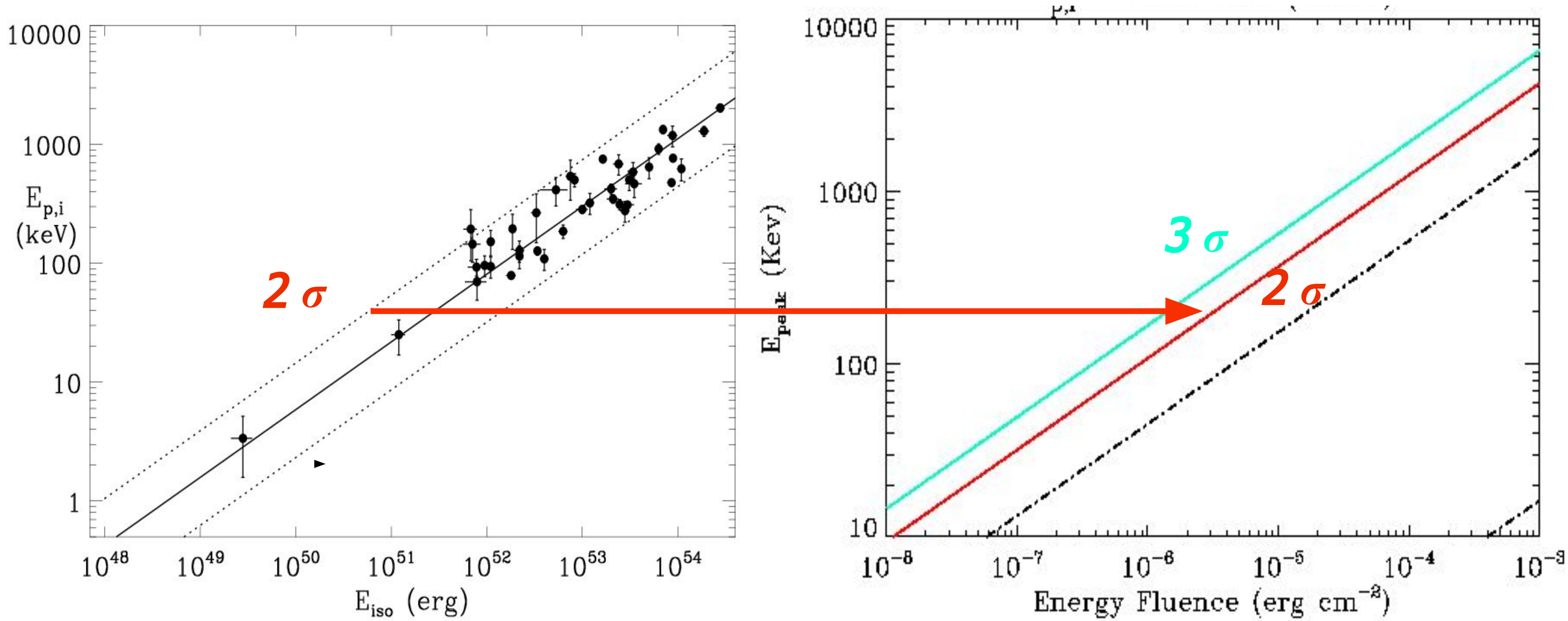
- in addition: Ghirlanda et al. (2005), Bosnjak et al. (2005), Nava et al. (2008), Ghirlanda et al. (2009) showed that **most** BATSE GRBs with unknown redshift **are potentially consistent** with the **correlation**

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

- **using GRBs with unknown redshift** -> convert the Ep,i – Eiso correlation into an Ep,obs – Fluence correlation

Intrinsic (cosm. Rest-frame) plane

Observer's plane



GRBs WITH redshift (130)

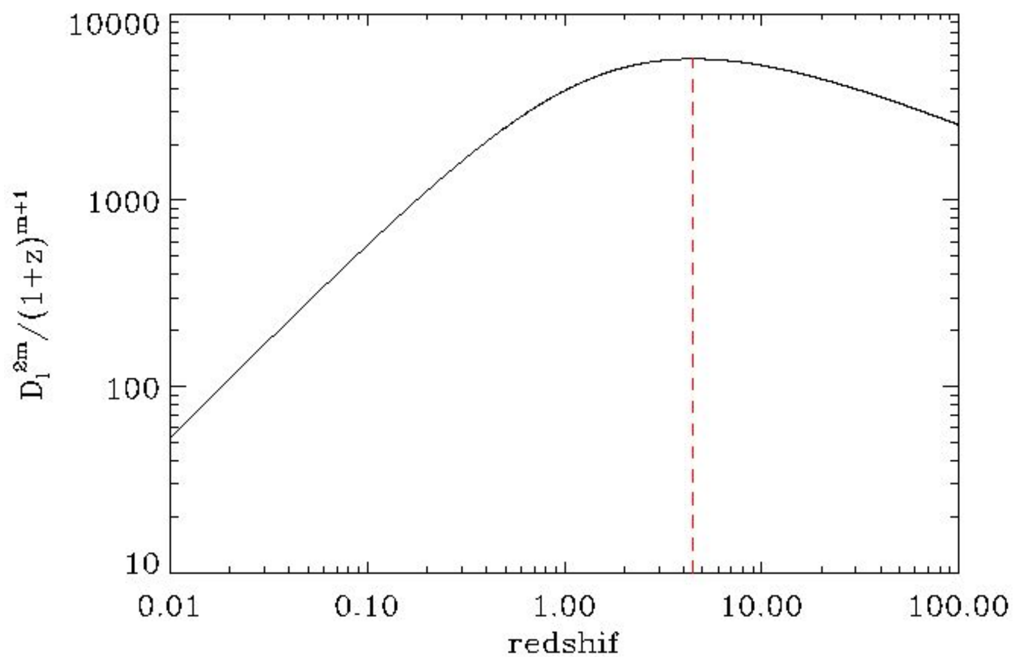
GRBs WITHOUT redshift (thousands)

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

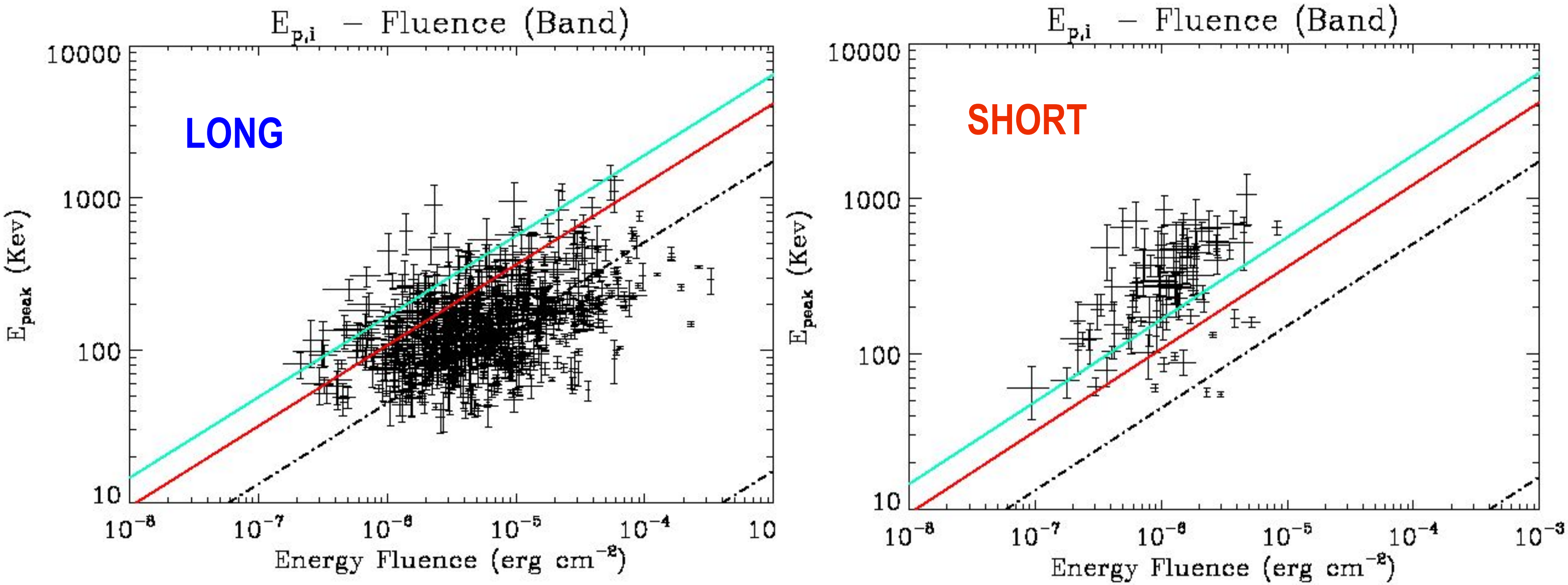
$$E_{\rm peak}^{\rm obs}(1+z) = k\left(\frac{4\pi d_{\rm L}^2 F}{1+z}\right)^a \rightarrow E_{\rm peak}^{\rm obs} = kF^a f(z); \qquad f(z) = \frac{(4\pi d_{\rm L}^2)^a}{(1+z)^{1+a}}$$

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

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

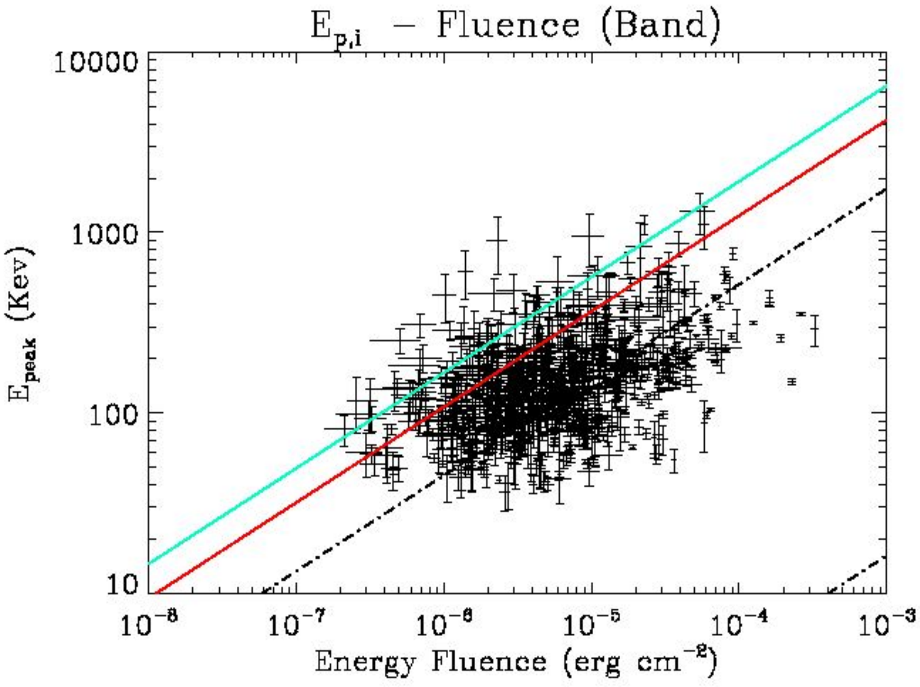


- Amati, Dichiara et al. (2013, in prep.): consider fluences and spectra from the Goldstein et al. (2010) BATSE complete spectral catalog (on line data)
- considered long (777) and short (89) GRBs with fit with the Band-law and uncertainties on Ep and fluence < 40%

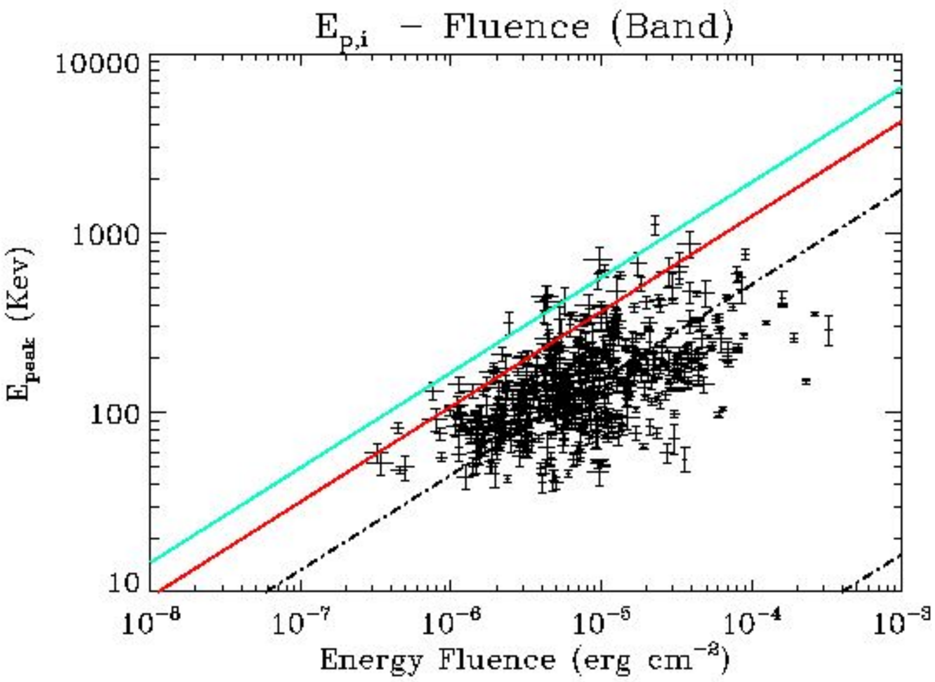


- **most long GRBs are potentially consistent with the Ep.i – Eiso correlation, most short GRBs are not**

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

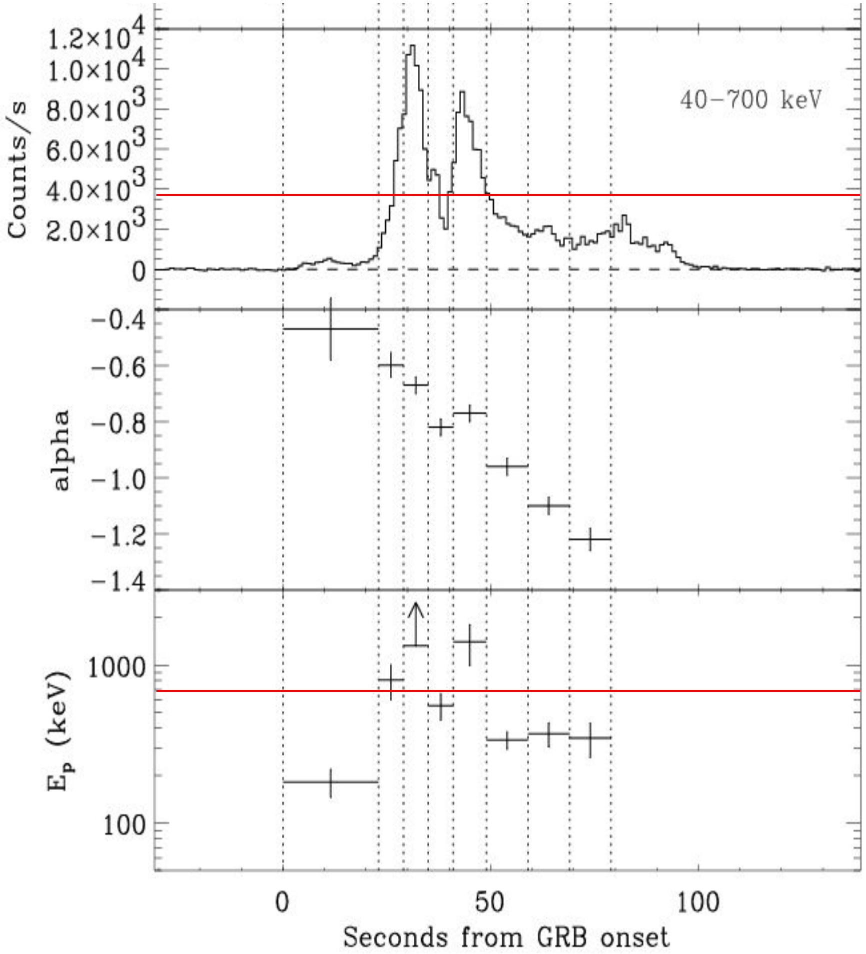


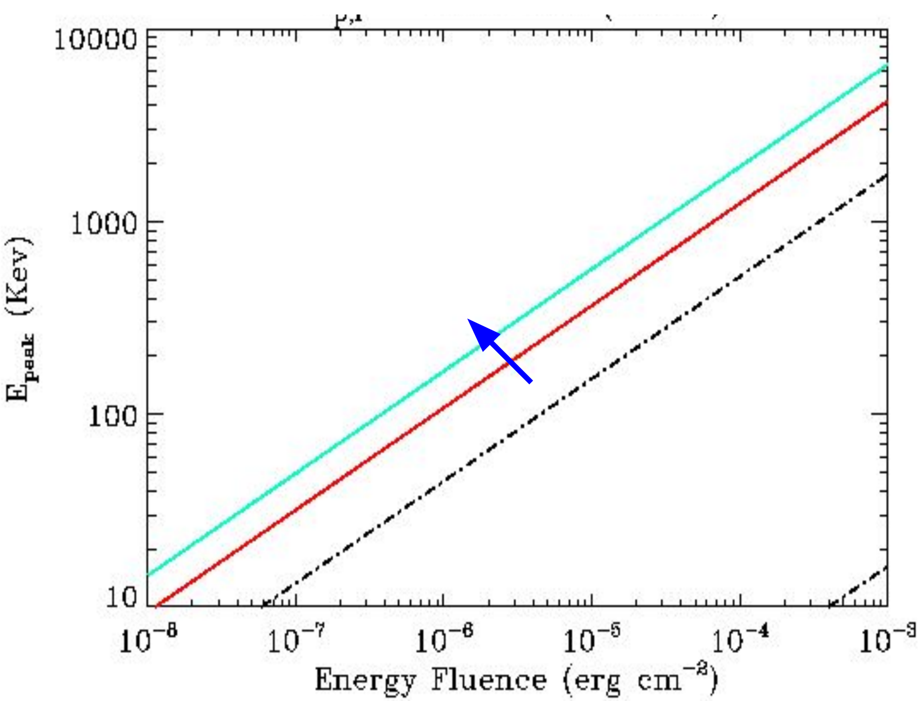
LONG, 40% unc.



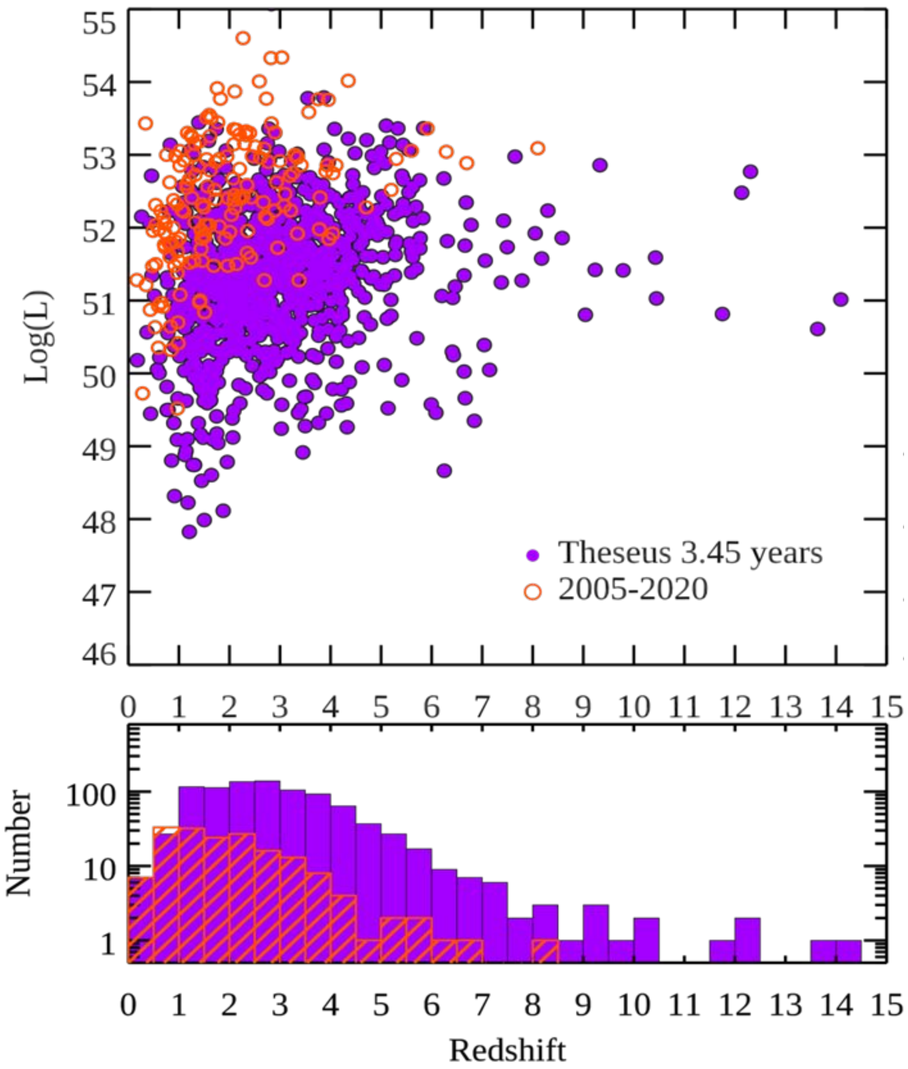
LONG, 20% unc.

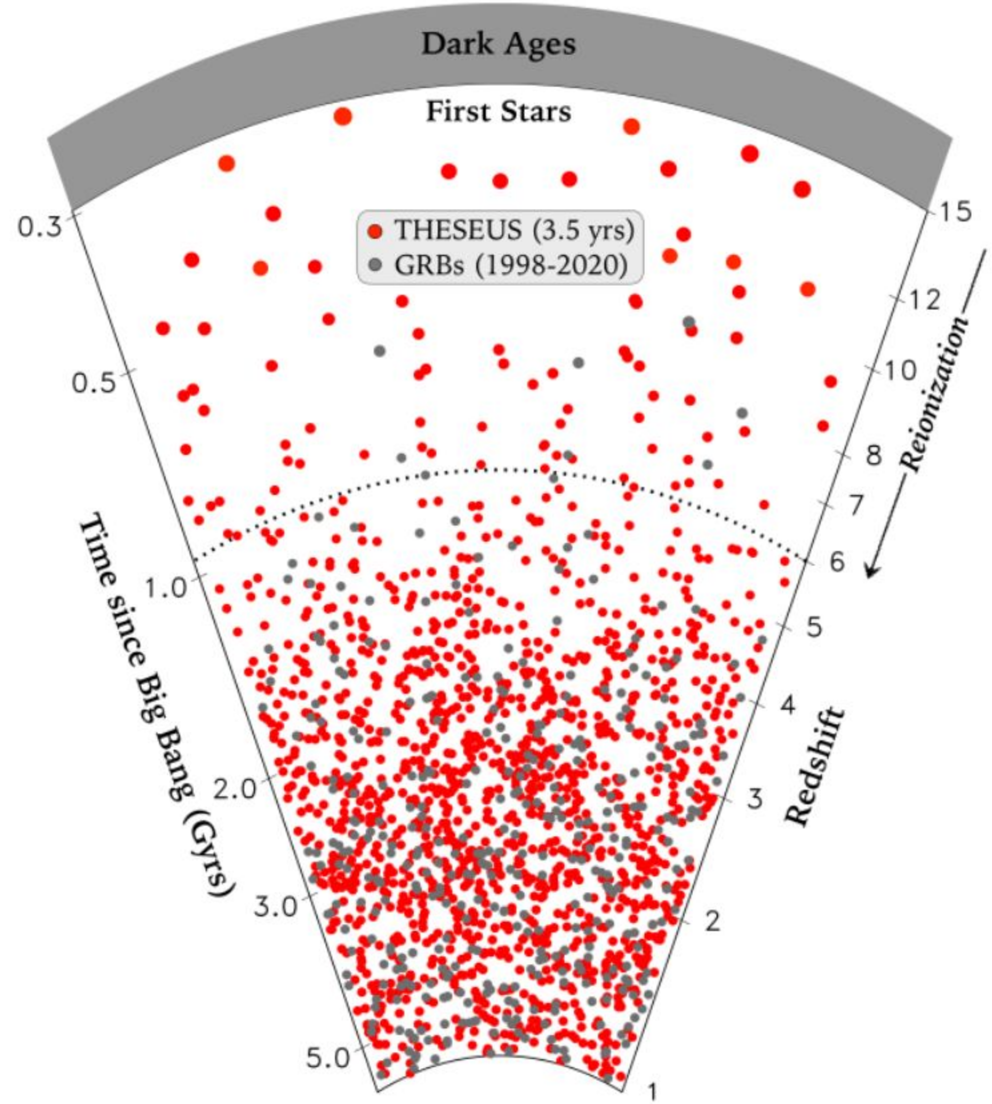
- measure only the harder portion of the event: overestimate of Ep and underestimate of the fluence



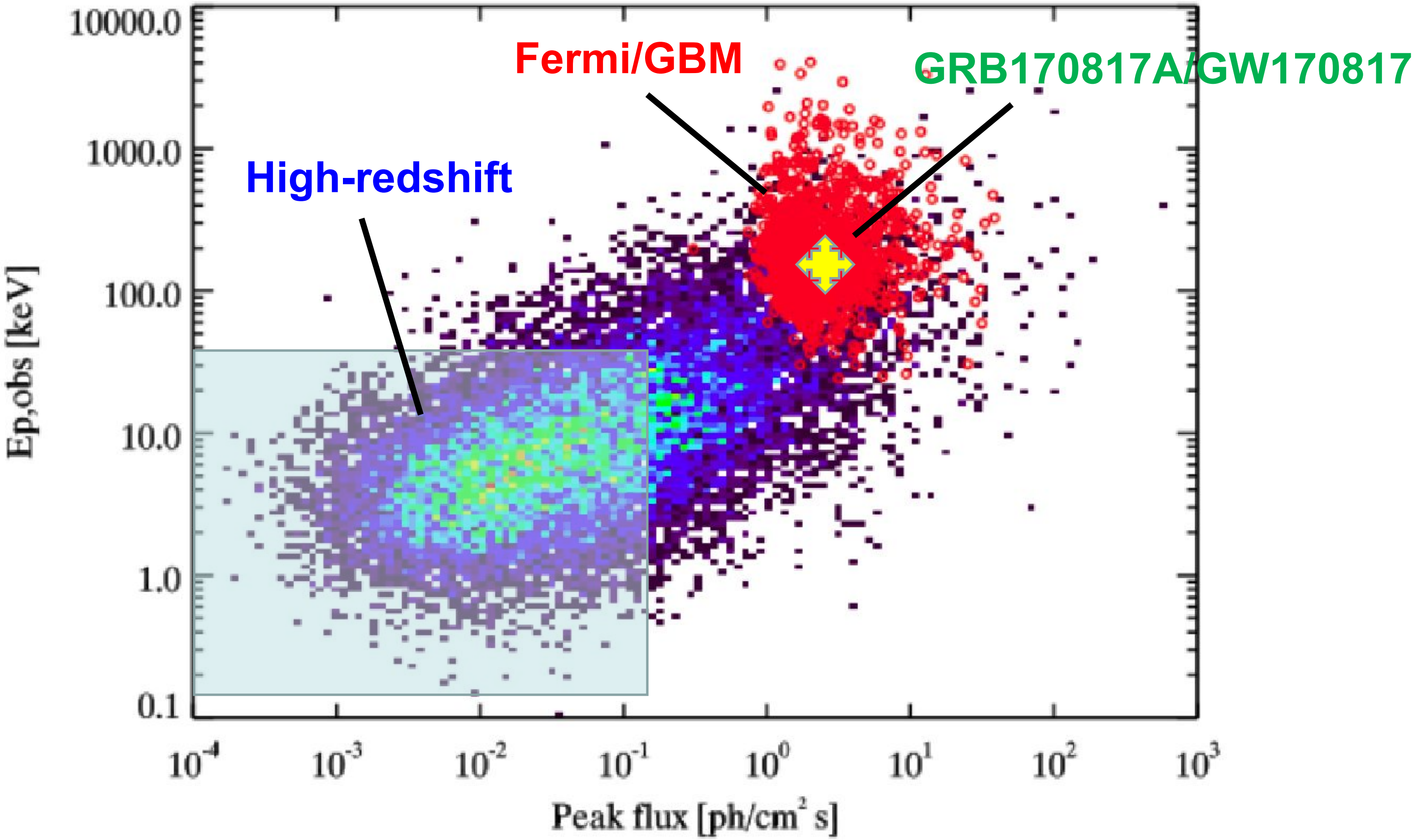


THESEUS: giant leap in GRB redshifts

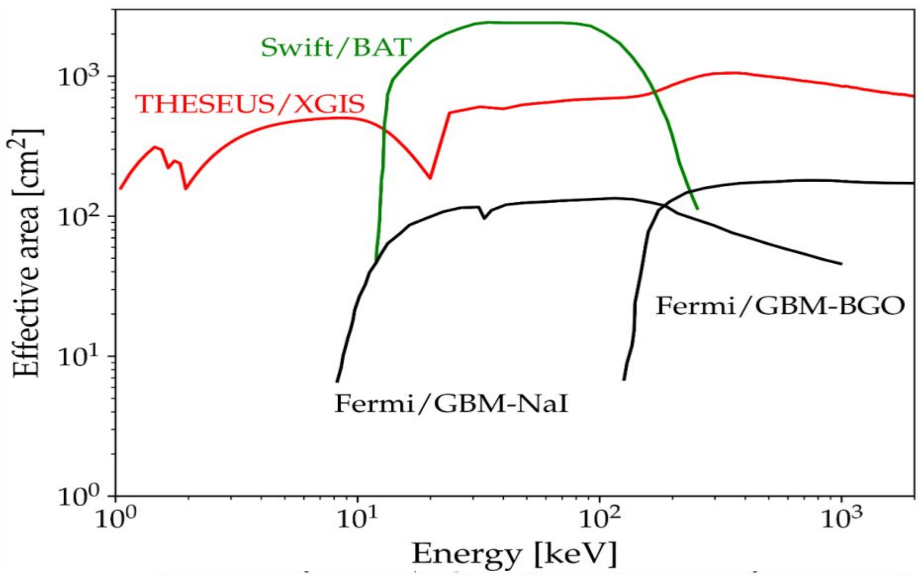


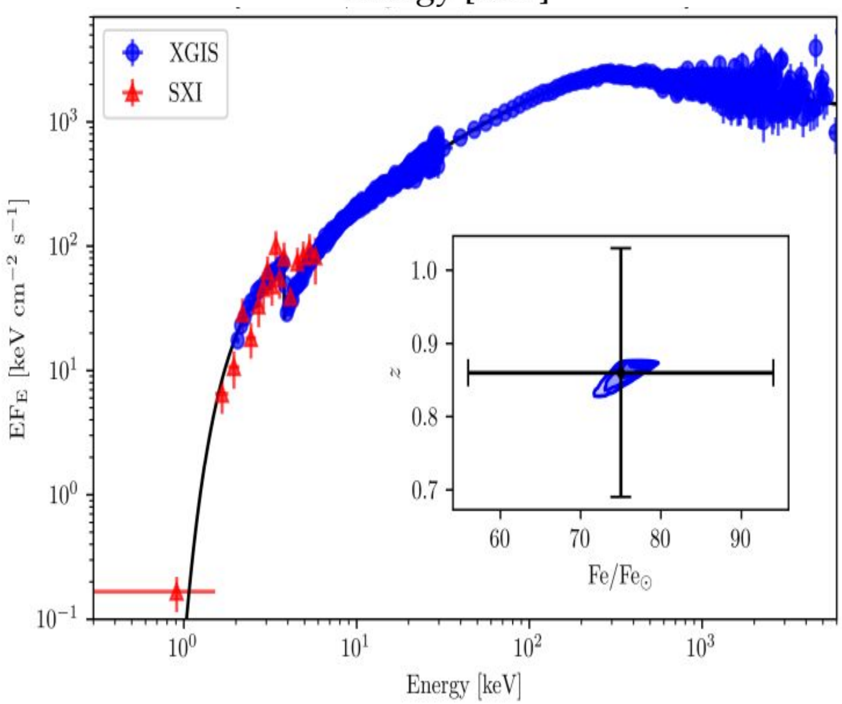


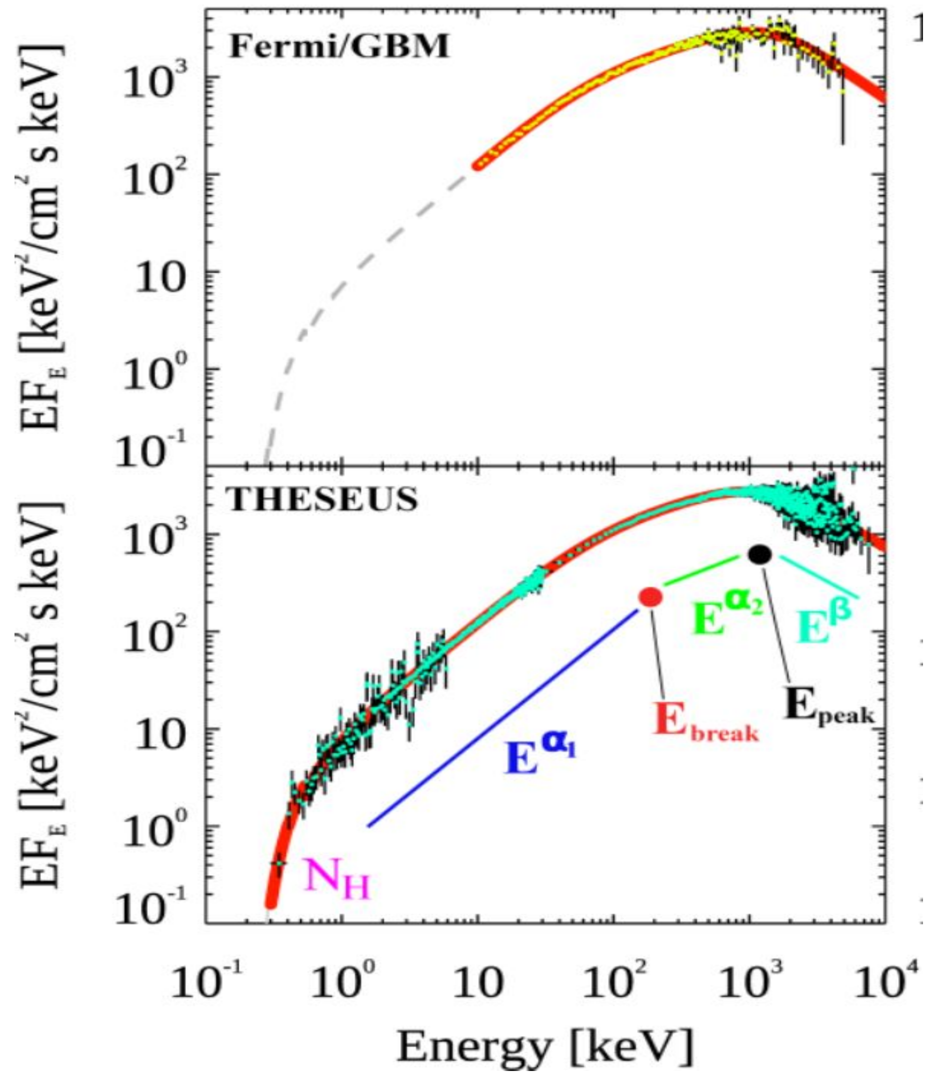
THESEUS will have the ideal combination of instrumentation and mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), providing accurate location and redshift for a large fraction of them



THESEUS: unprecedented spectroscopy of GRB





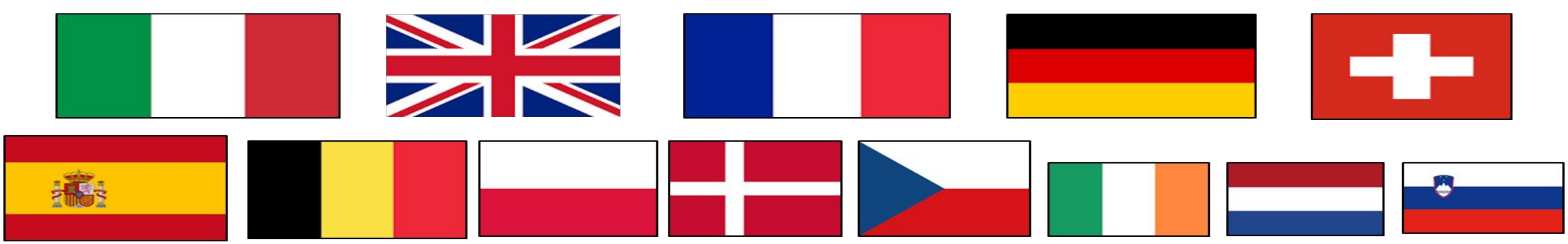


THESEUS
Transient High Energy Sky and Early Universe Surveyor

Lead Proposer (ESA/M5): Lorenzo Amati (INAF – OAS Bologna, Italy)

Coordinators (ESA/M5): Lorenzo Amati, Paul O’Brien (Univ. Leicester, UK), Diego Gotz (CEA-Paris, France), A. Santangelo (Univ. Tuebingen, D), E. Bozzo (Univ. Genève, CH)

Payload consortium: Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Belgium, Czech Republic, Slovenia, Ireland, NL, ESA

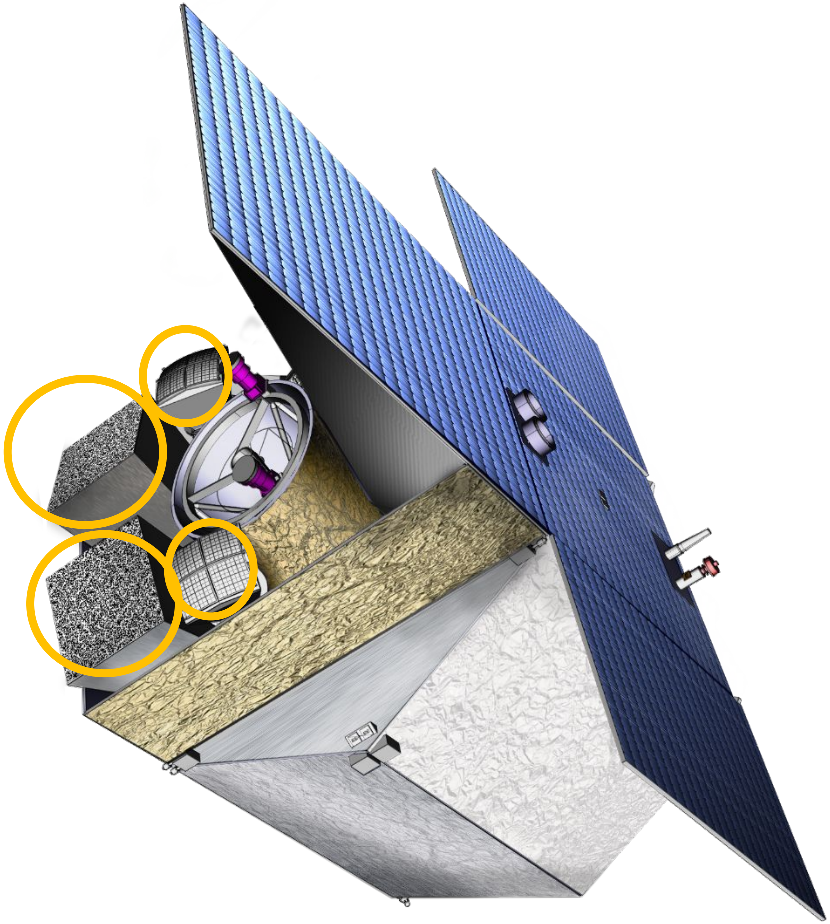


Future GRB missions: the case of THESEUS

(led by Italy; ESA/M5 Phase-A study, re-proposed for M7)

THIS BREAKTHROUGH WILL BE ACHIEVED BY A MISSION CONCEPT OVERCOMING MAIN LIMITATIONS OF CURRENT FACILITIES

Set of innovative wide-field monitors with **unprecedented combination of broad energy range, sensitivity, FOV and localization accuracy**



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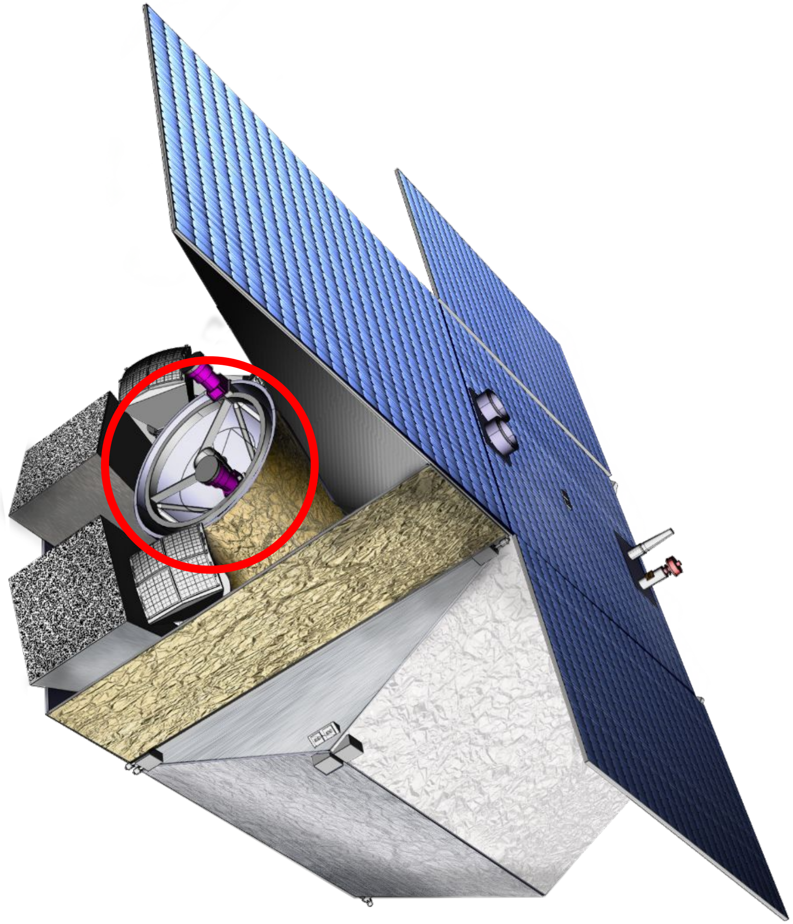
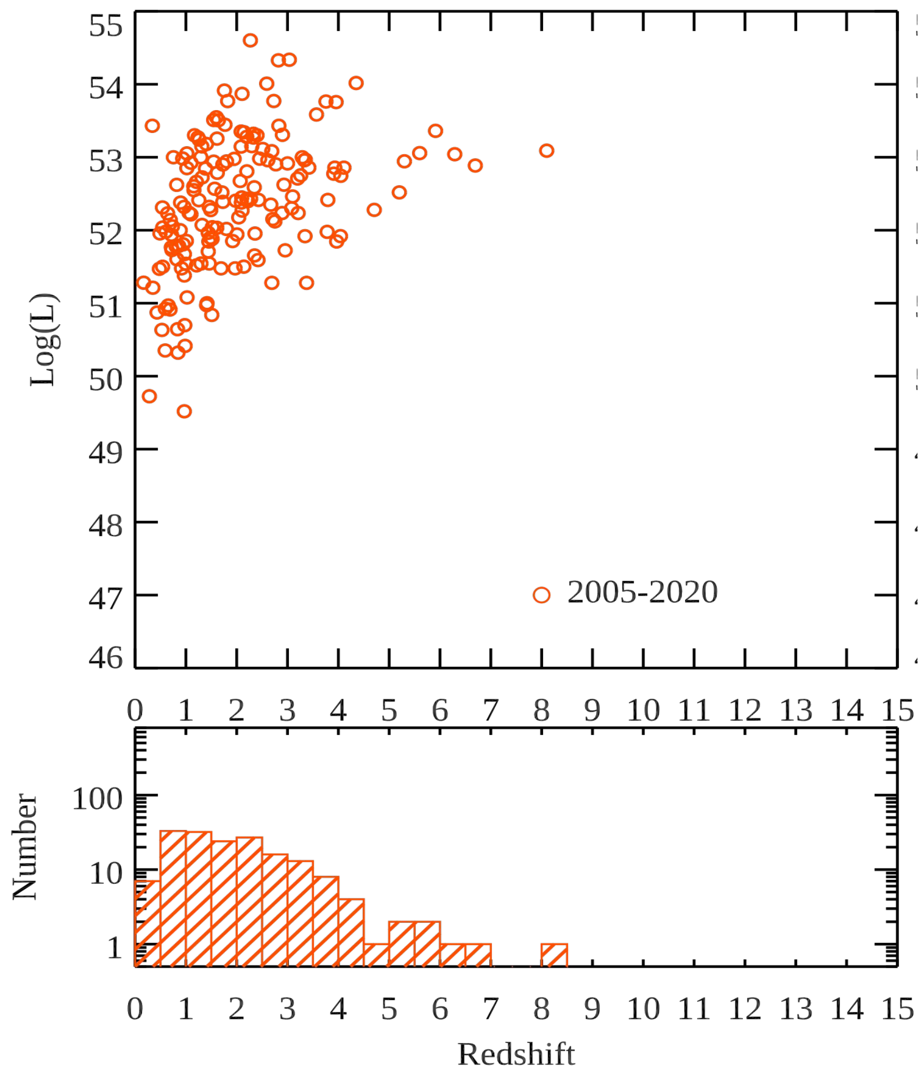
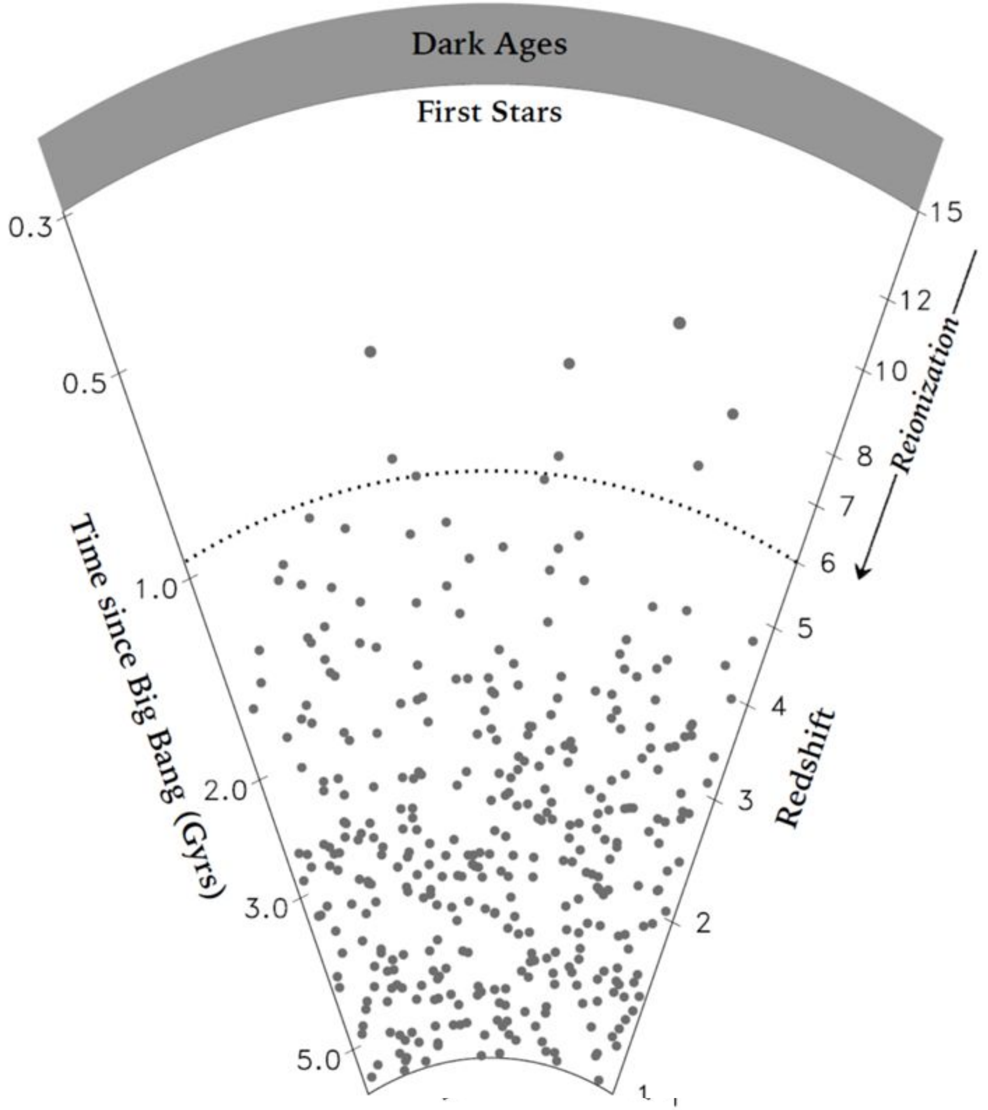
On-board **autonomous fast follow-up** in optical/NIR, arcsec location and **redshift measurement** of detected GRB/transients

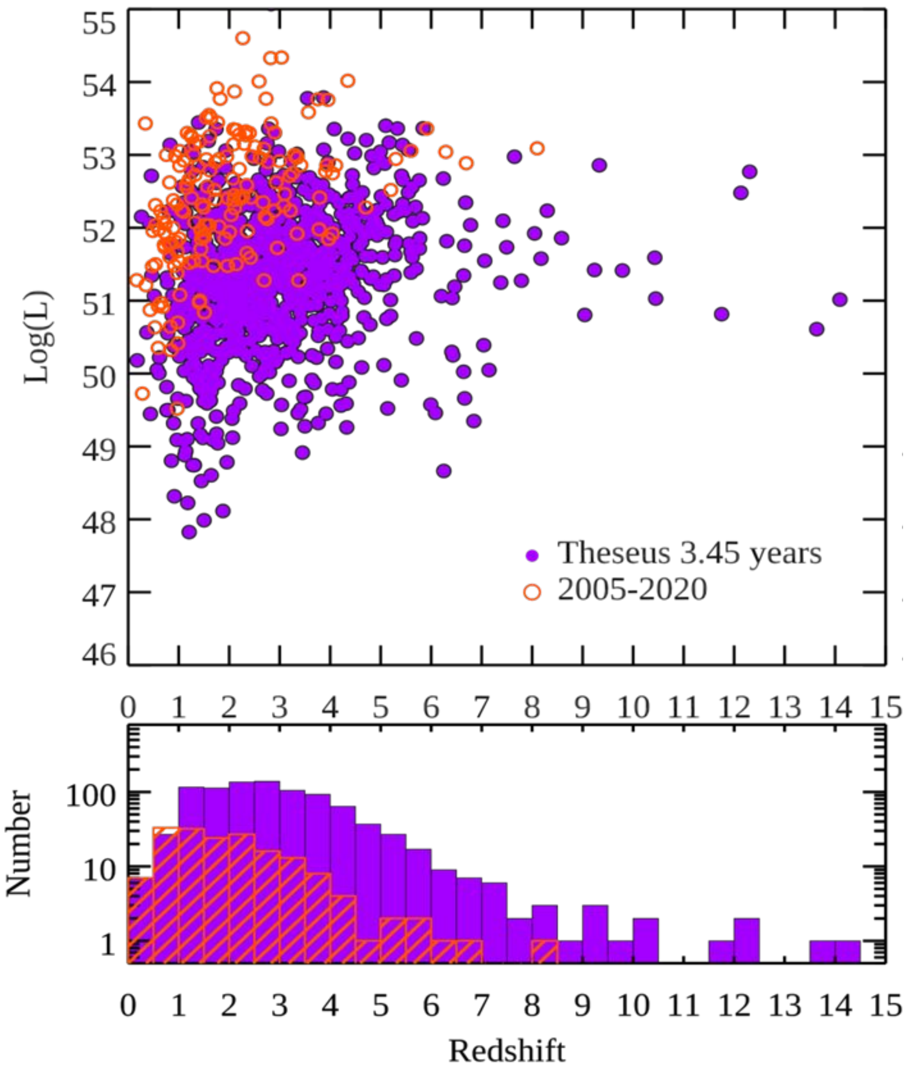


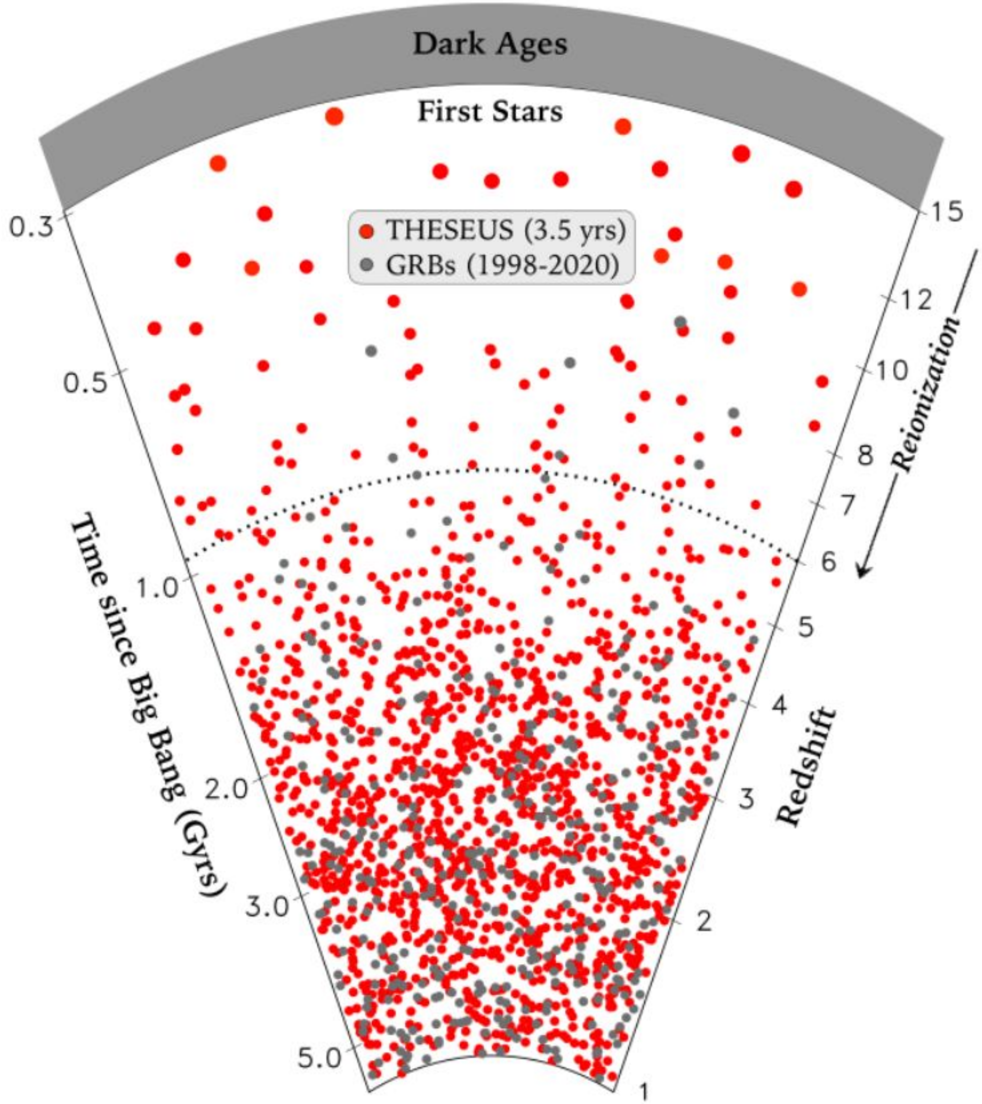
Shedding light on the early Universe with GRBs





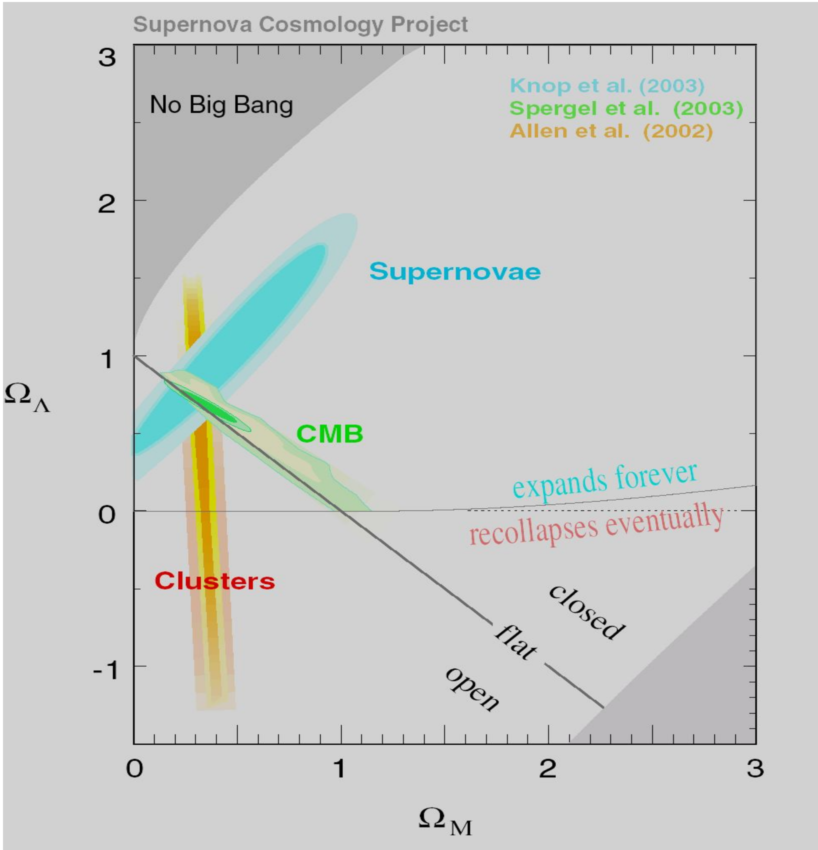
Shedding light on the early Universe with GRBs

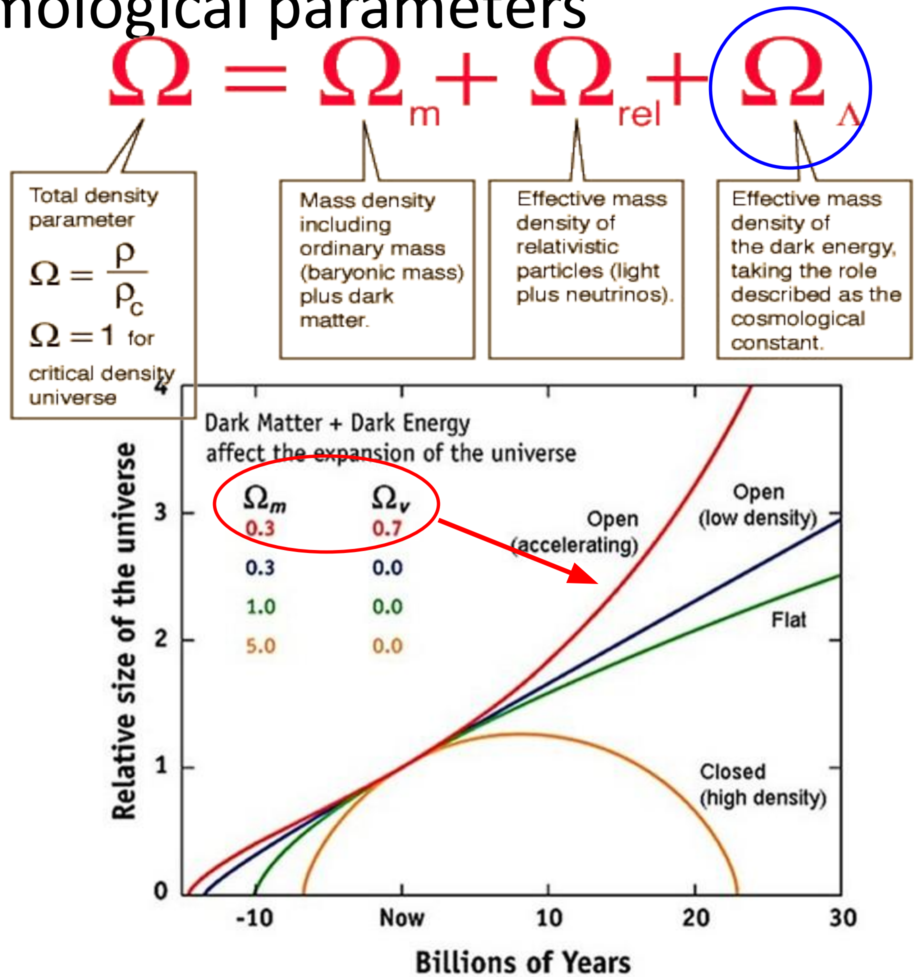




Why looking for more cosmological probes ?

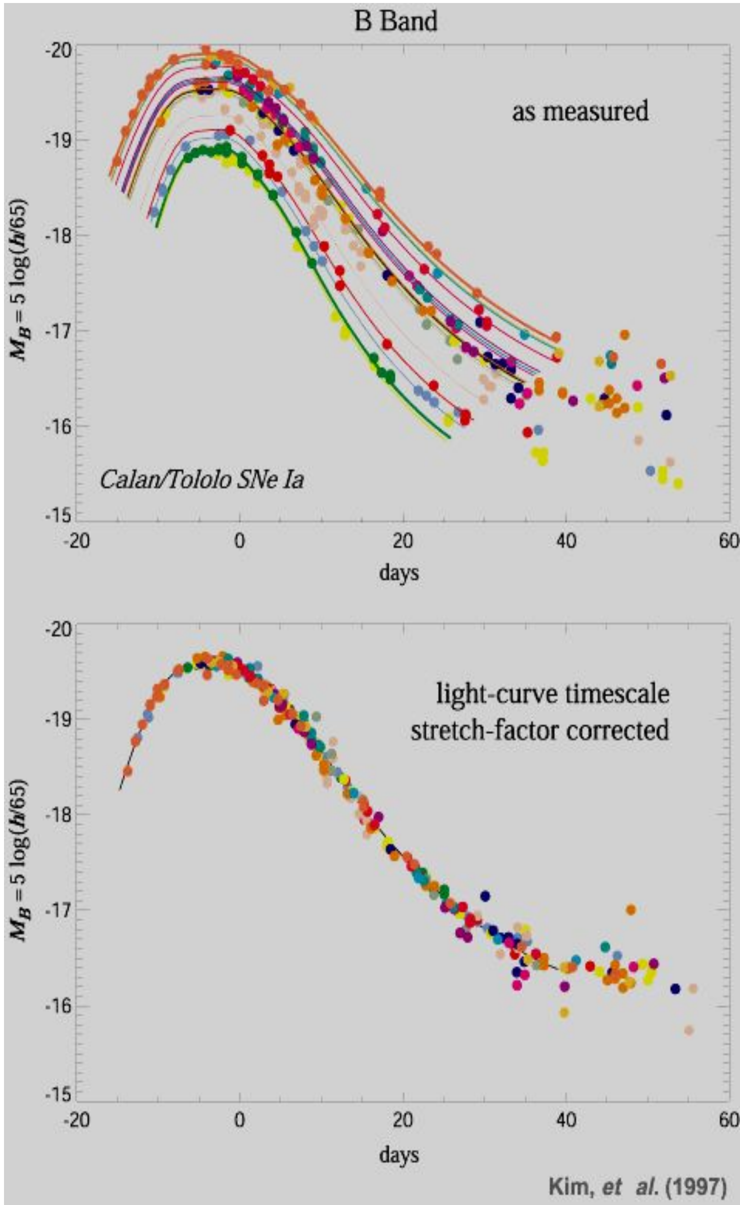
- different distribution in redshift and methods-> different sensitivity to different cosmological parameters



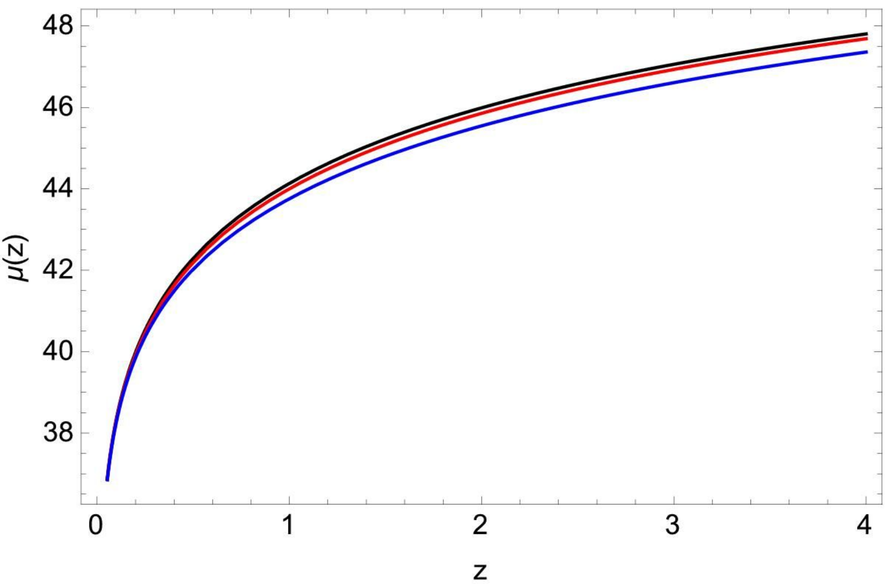


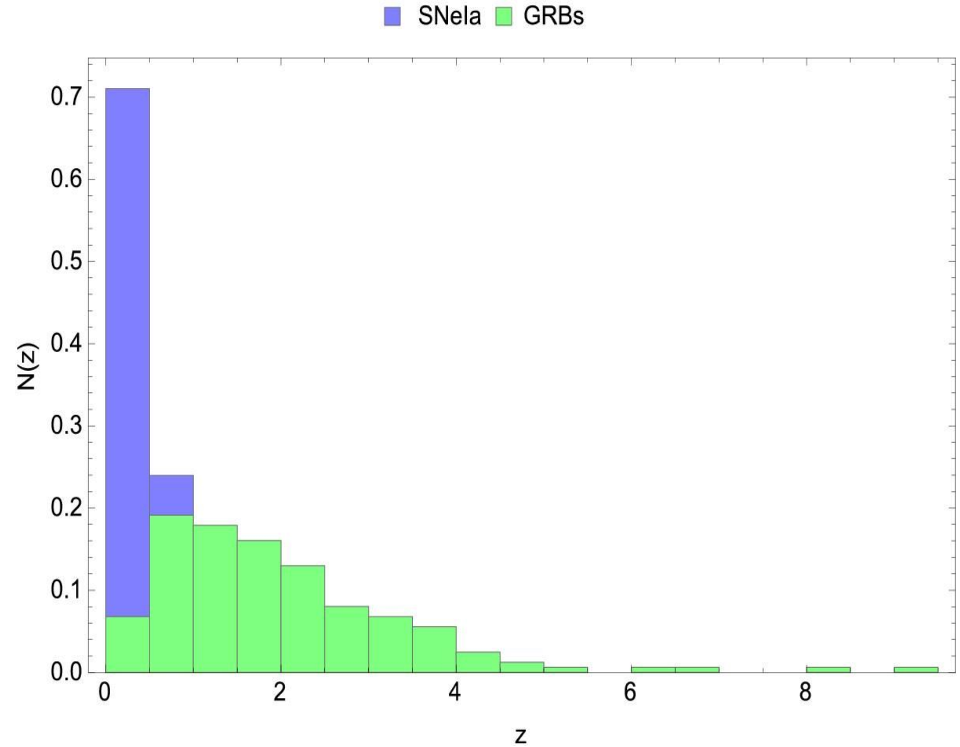
$$D_L = (1+z)c \div H_o \, |k|^{0.5} \times S\left\{ |k|^{0.5} \int_0^z \left[k(1+z)^2 + \Omega_M (1+z')^3 + \Omega_\Lambda \right]^{-0.5} dz' \right\}$$

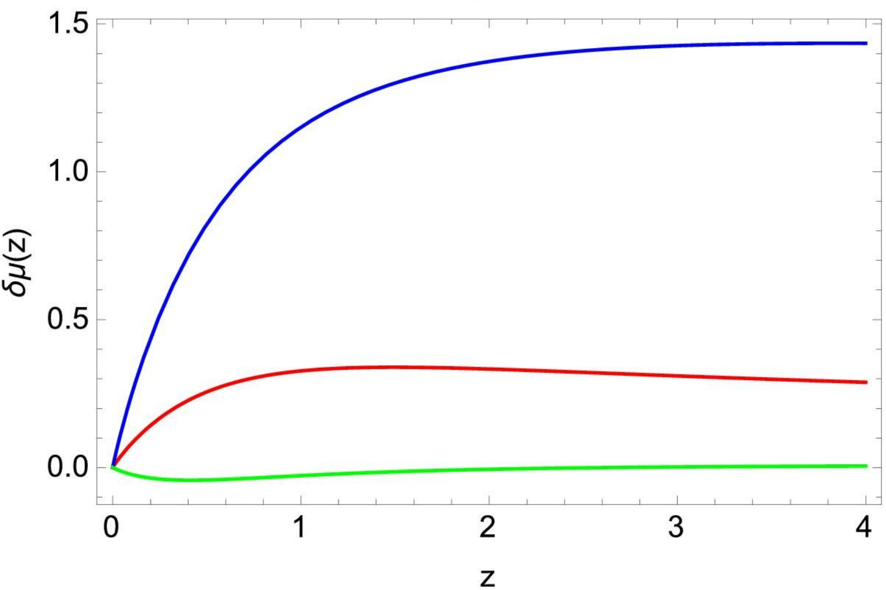
- **Each cosmological probe is characterized by possible systematics**
- **e.g SN Ia:**
  - different explosion mechanism and progenitor systems ? May depend on z ?
  - light curve shape correction for the luminosity normalisation may depend on z
  - signatures of evolution in the colours
  - correction 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)

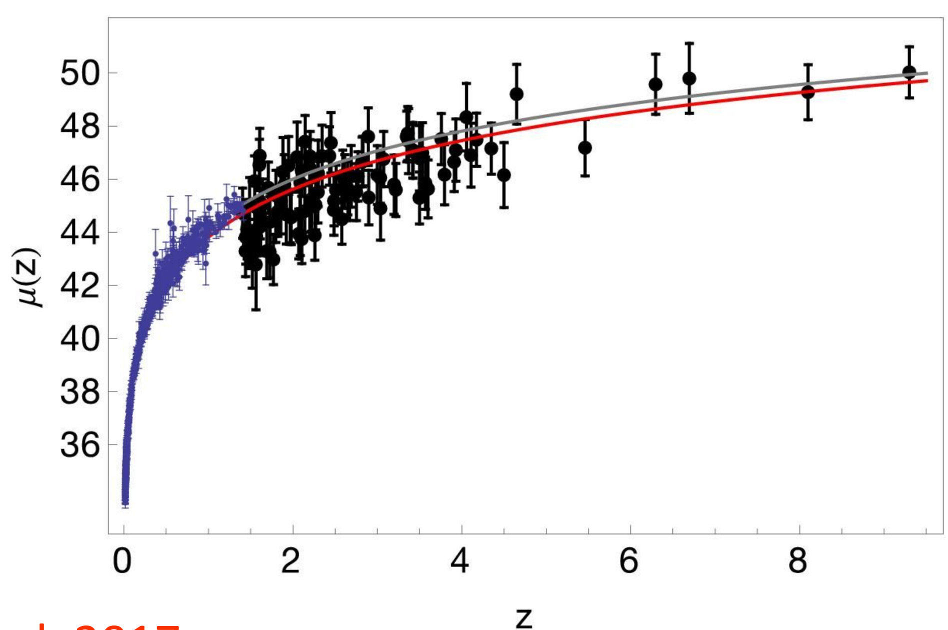


The power of GRBs





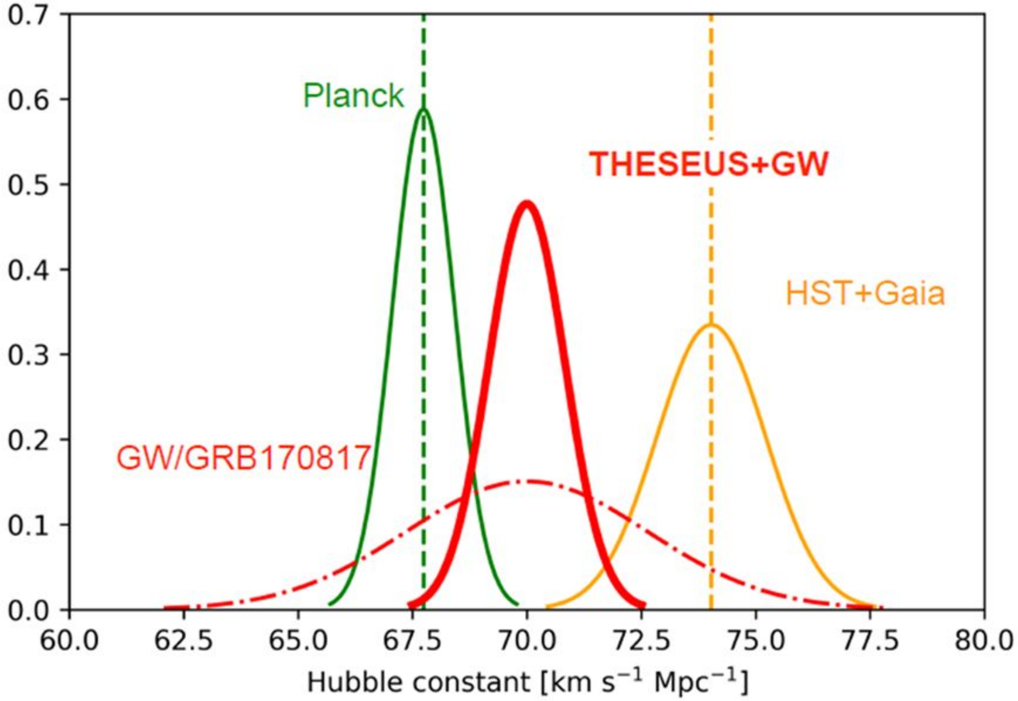


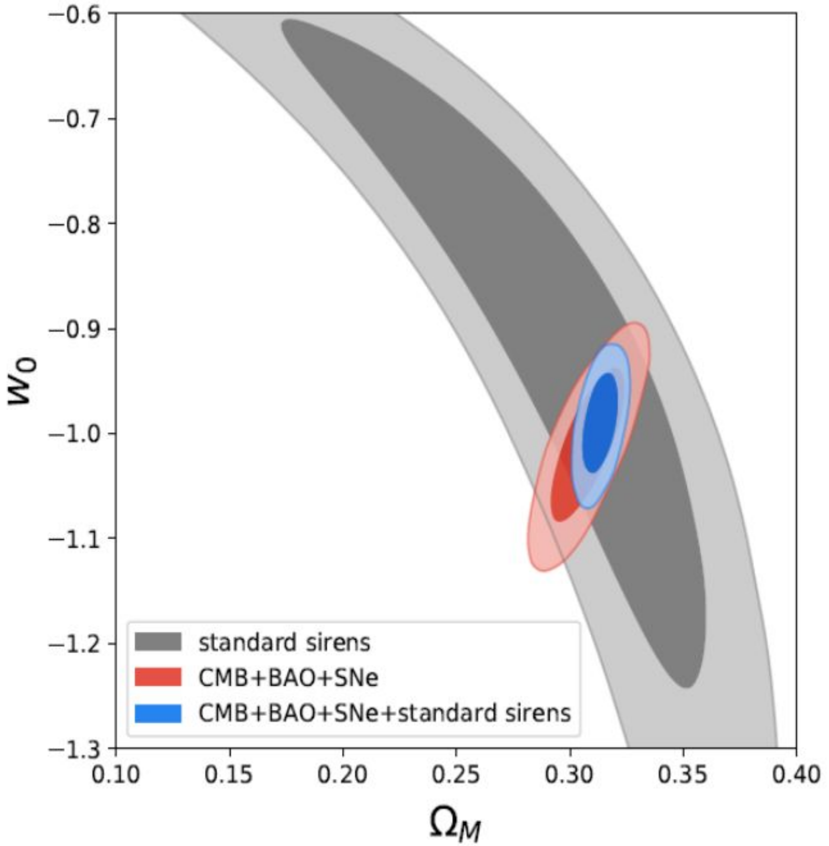


Demianski et al. 2017

Multi-messenger cosmology through GRBs

MEASURING THE EXPANSION RATE AND GEOMETRY OF SPACE-TIME





~20 joint GRB+GW events

Fundamental physics with GRBs: testing LI / QG

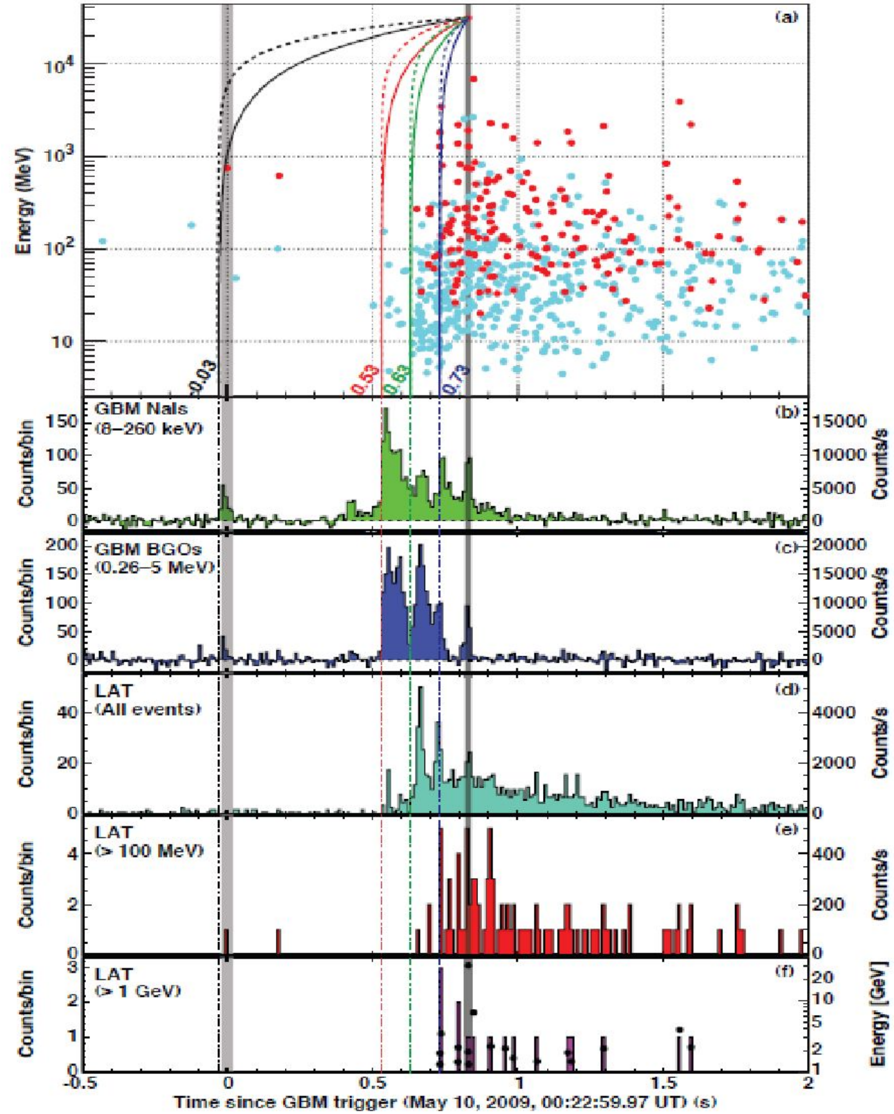
- Using time delay between low and high energy photons to put Limits on Lorentz Invariance Violation (allowed by unprecedent Fermi GBM + LAT broad energy band)

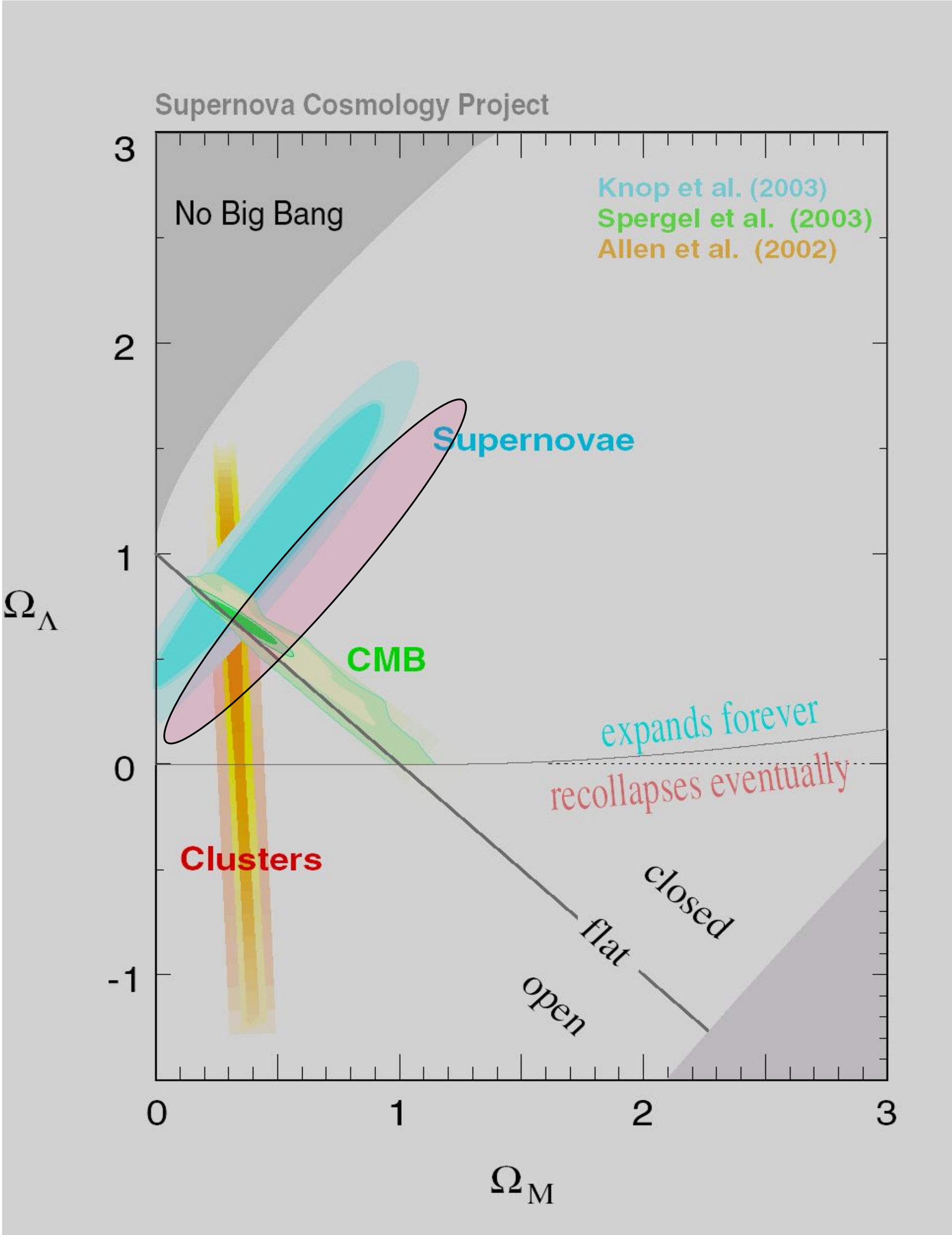
$$v_{\rm ph} = \frac{\partial E_{\rm ph}}{\partial p_{\rm ph}} \approx c\left[1 - s_n \frac{n+1}{2}\left(\frac{E_{\rm ph}}{M_{{\rm QG},n}c^2}\right)^n\right]$$

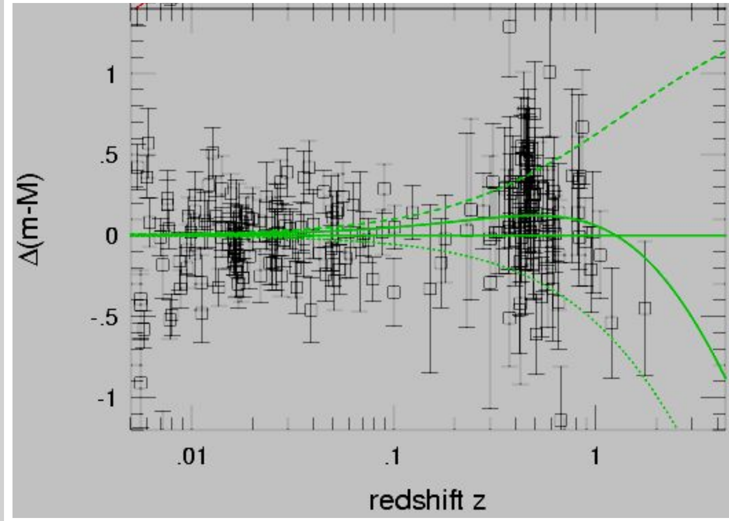
$$\Delta t = s_n \frac{(1+n)}{2H_0} \frac{(E_h^n - E_l^n)}{(M_{{\rm QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}}\, dz'$$

GRB 990510 $E_h = 30.53^{+5.79}_{-2.56}$ GeV

$t_{\rm start}$ (ms)	limit on $\lvert\Delta t\rvert$ (ms)	Reason for choice of $t_{\rm start}$ or limit on Δt	E_l (MeV)	valid for s_n	lower limit on $M_{\rm QG,1}/M_{\rm Planck}$
−30	< 859	start of any observed emission	0.1	1	> 1.19
530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
630	< 199	start of > 100 MeV emission	100	1	> 5.12
730	< 99	start of > 1 GeV emission	1000	1	> 10.0
—	< 10	association with < 1 MeV spike	0.1	±1	> 102
—	< 19	if 0.75 GeV γ is from 1st spike	0.1	±1	> 1.33
$\lvert\frac{\Delta t}{\Delta E}\rvert < 30\ \frac{\rm ms}{\rm GeV}$		lag analysis of all LAT events	—	±1	> 1.22





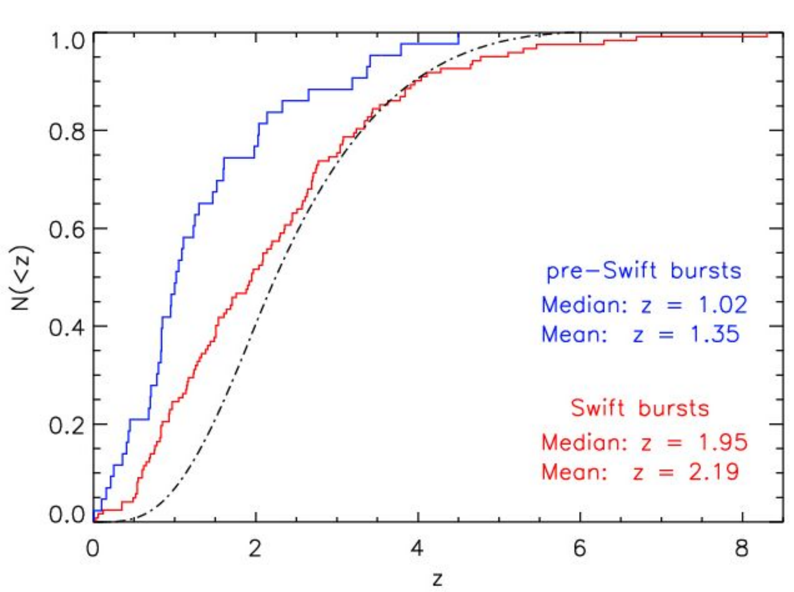


If the "offset from the truth" is just 0.1 mag….

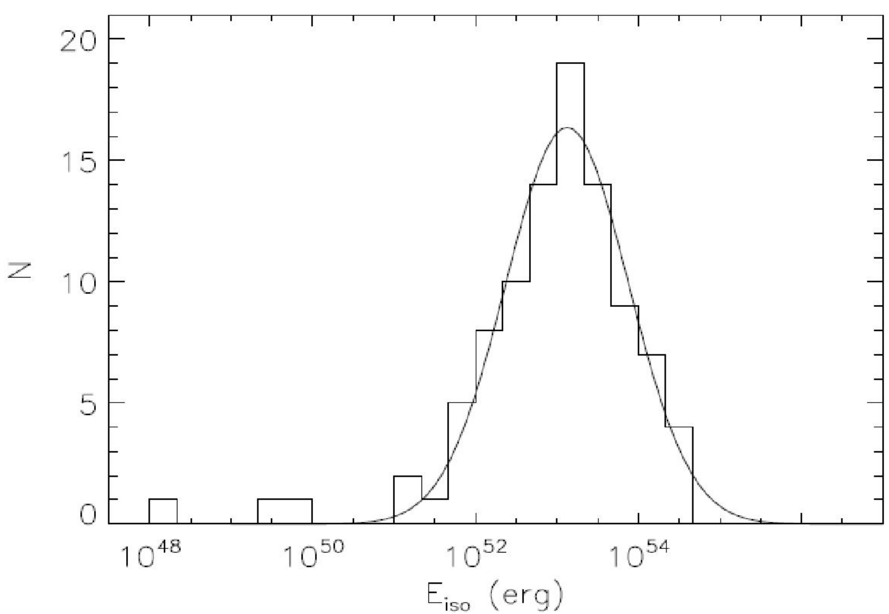
(slide by M. della Valle)

Are Gamma-Ray Bursts standard candles ?

- all GRBs with measured redshift (~400, including a few short GRBs) lie at cosmological distances **(z = 0.033 – ~9.3**) (except for the peculiar GRB980425, z=0.0085)
- isotropic **luminosities and radiated energy are huge**, can be detected up to very high z
- no dust extinction problems; z distribution much beyond SN Ia **but… GRBs are not standard candles (unfortunately)**



Jakobsson et al., 2010



Amati, 2009

Perspectives

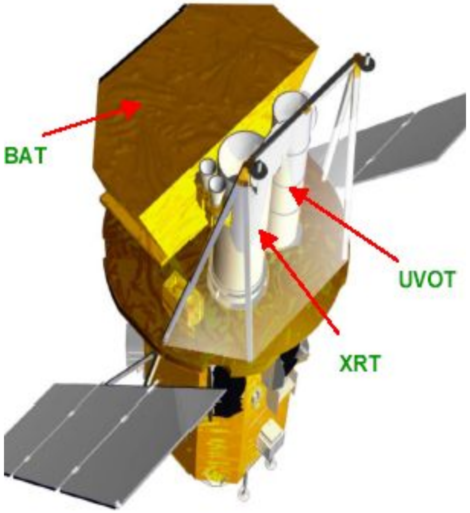
- **present and near future: main contribution expected from joint Fermi + Swift measurements**

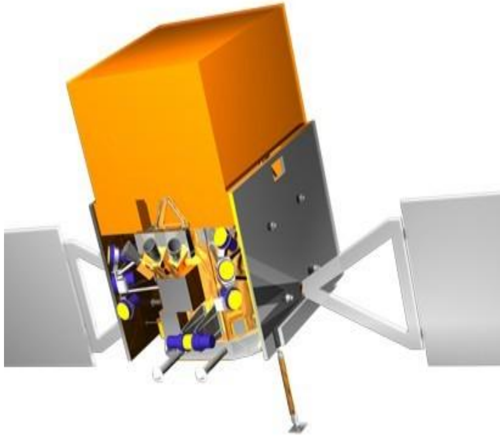
 - Up to 2009: ~290 Fermi/GBM GRBs, Ep estimates for ~90%, ~35 simultaneously detected by Swift (~13%), 13 with **Ep and z** estimates **(~10% of Swift sample)**

 - 2008 pre-Fermi : 61 Swift detections, 5 BAT Ep (8%), 15 BAT + KONUS + SUZAKU Ep estimates (25%), 20 redshift (33%), 11 with **Ep and z** estimates **(~15% of Swift sample)**

 - Fermi provides a dramatic increase in Ep estimates (as expected), but a only small fraction of Fermi GRBs is detected / localized by Swift (~15%) -> **low number of Fermi GRBs with Ep and z (~5%)**.

 - **Summary: 15-20 GRB/year in the Ep,i – Eiso plane**





❑ In the > 2020 time frame a significant step forward expected from SVOM (+ UFFO, CALET/GBM ?)

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

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

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

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