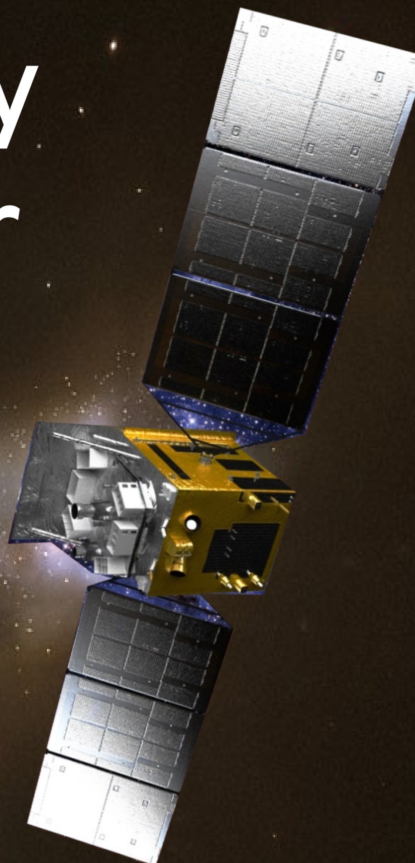
A joint spectral and temporal analysis of GRBs detected by HXMT and Swift-BAT and/or Fermi-GBM



Cristiano Guidorzi

on behalf of the Uni Ferrara + INAF Bologna GRB team

University of Ferrara

agenzia spaziale italiana

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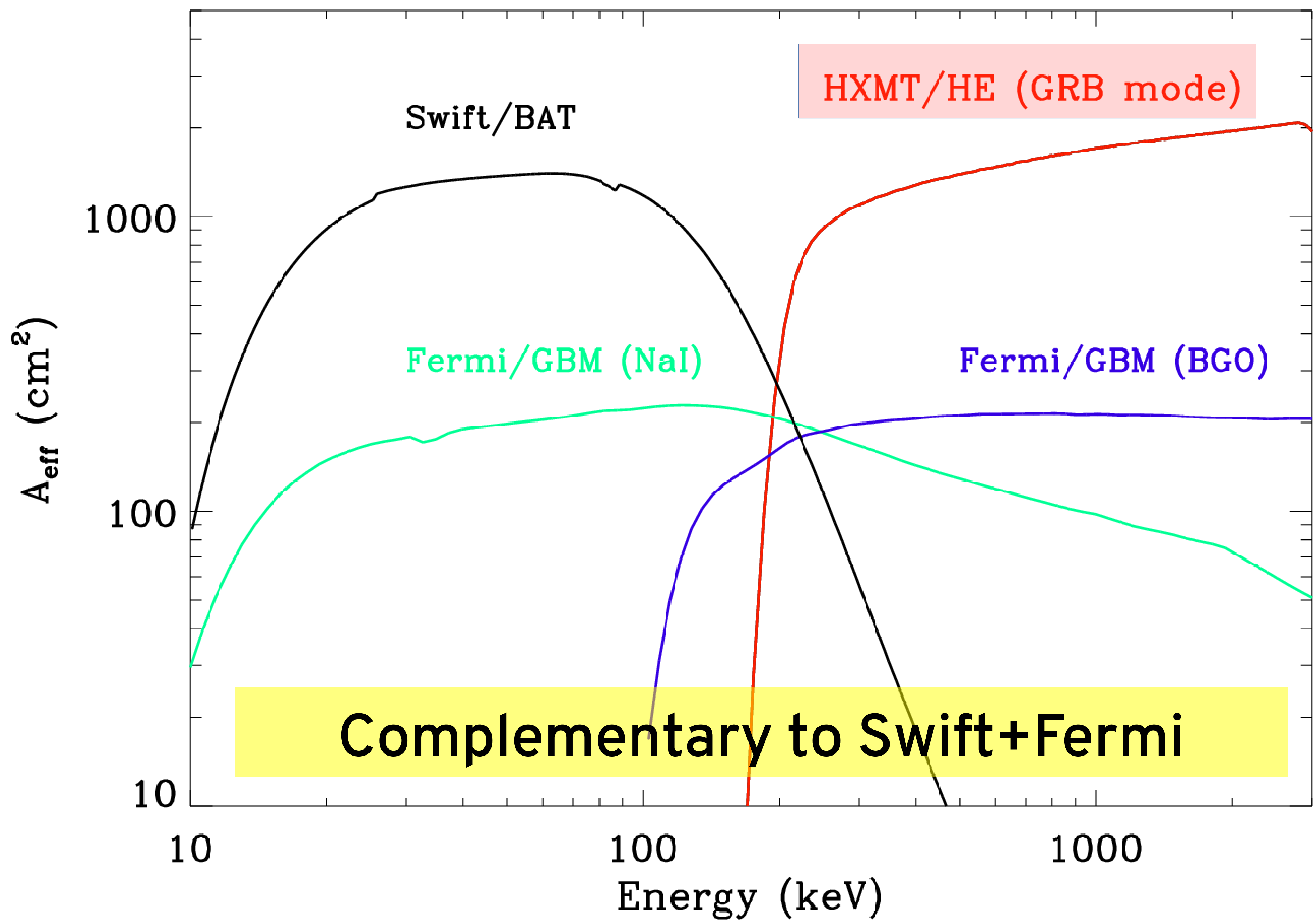
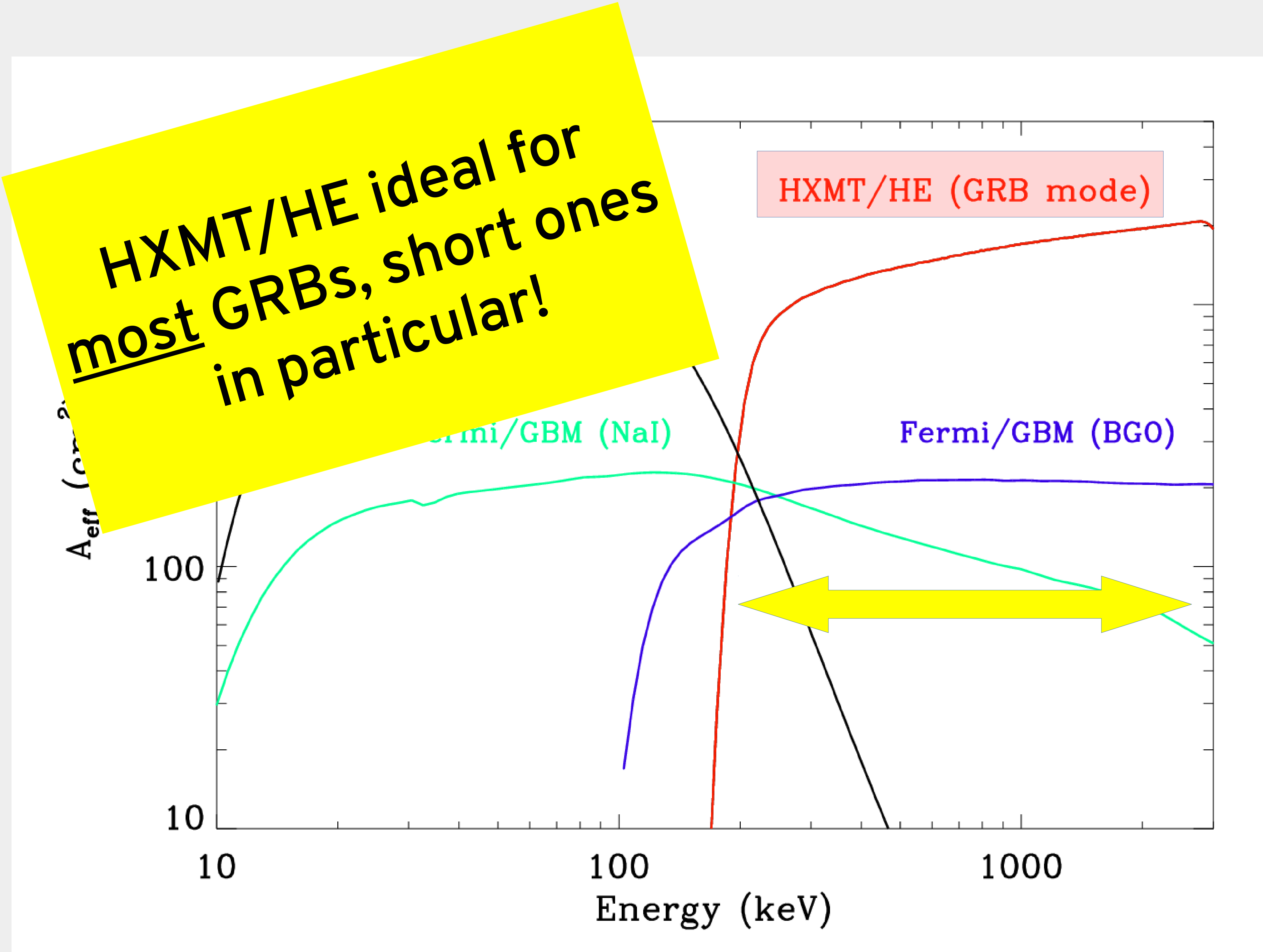


HXMT/HE (GRB mode)
Swift/BAT
Fermi/GBM (NaI)
Fermi/GBM (BGO)
Complementary to Swift+Fermi
1000
100
10
10
100
1000
Energy (keV)
A_{eff} (cm^2)


HXMT/HE ideal for most GRBs, short ones in particular!
HXMT/HE (GRB mode)
Fermi/GBM (BGO)
rmi/GBM (NaI)
100
10
10
100
1000
Energy (keV)
A_{eff}

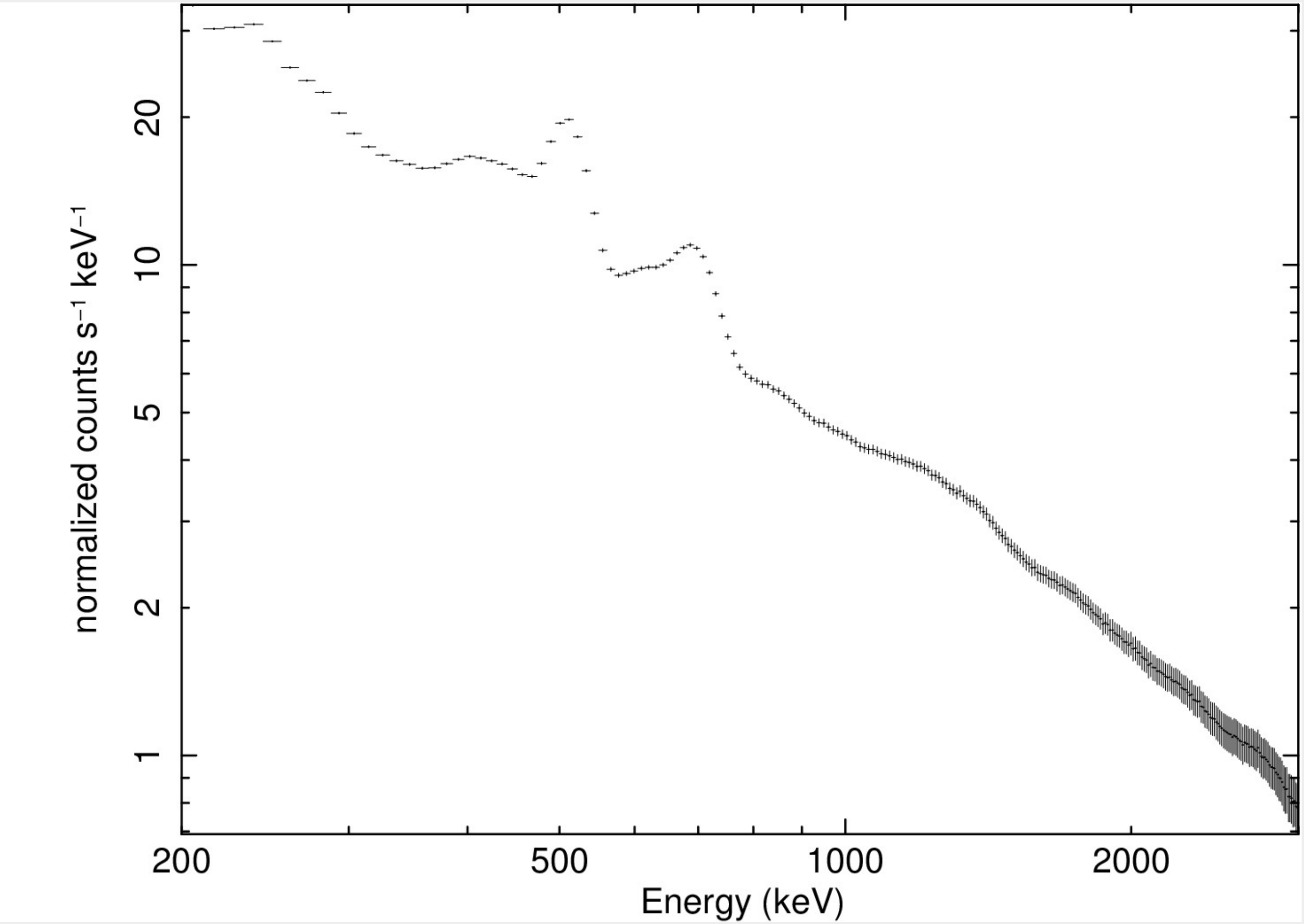
Simulated HXMT spectra and light curves

Simulations

Direction: 135 deg (rear)
HE mode: GRB

Background:

- total 18 CsI units
- 20 keV – 3 MeV
- 256 energy chan
- Includes:
  - CXB
  - Primary & albedo p+/e+/e-
  - albedo gamma
  - SAA proton -activ fluorescence

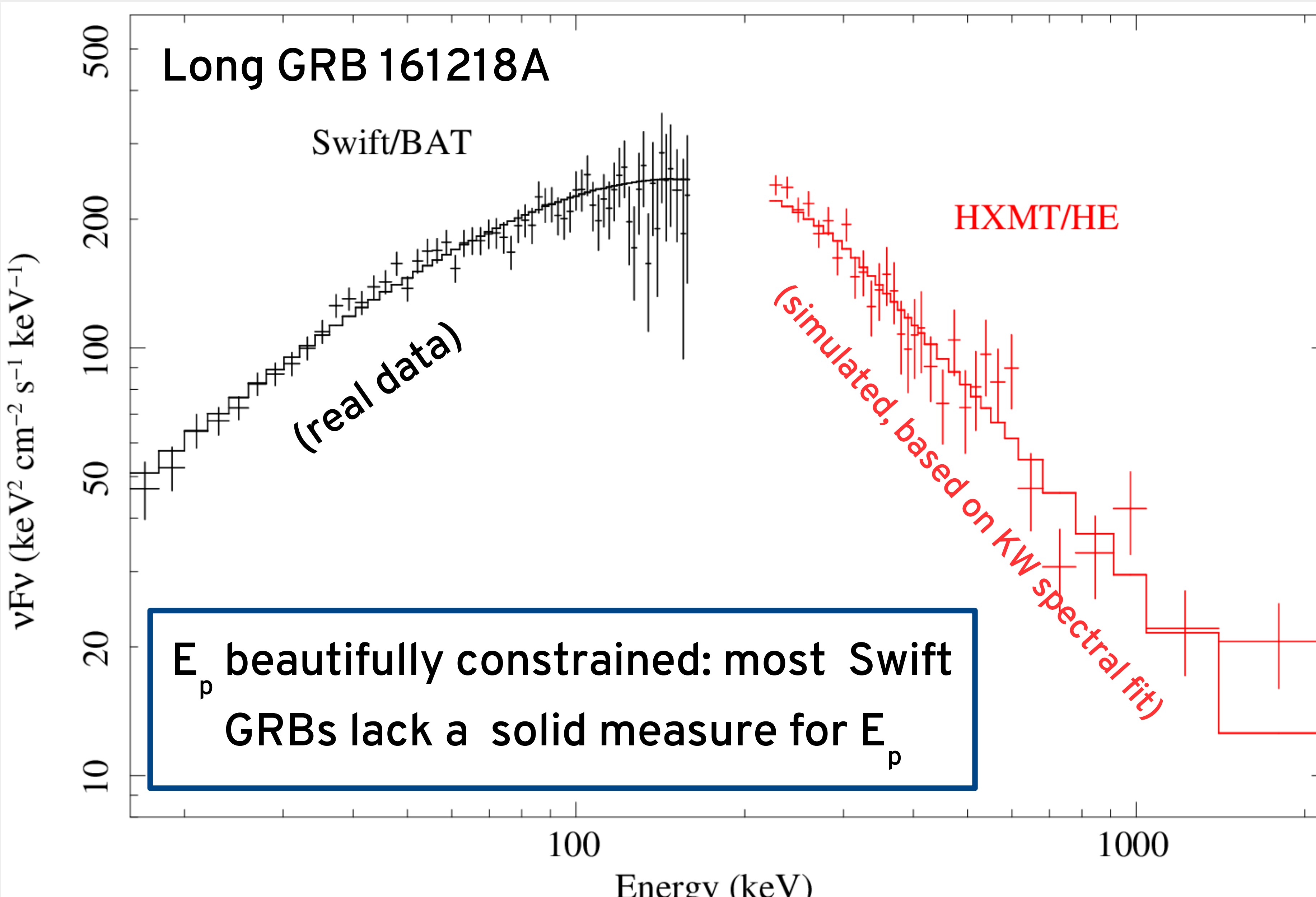


Estimated full-band background C/R: ~ **14,000 counts/s**

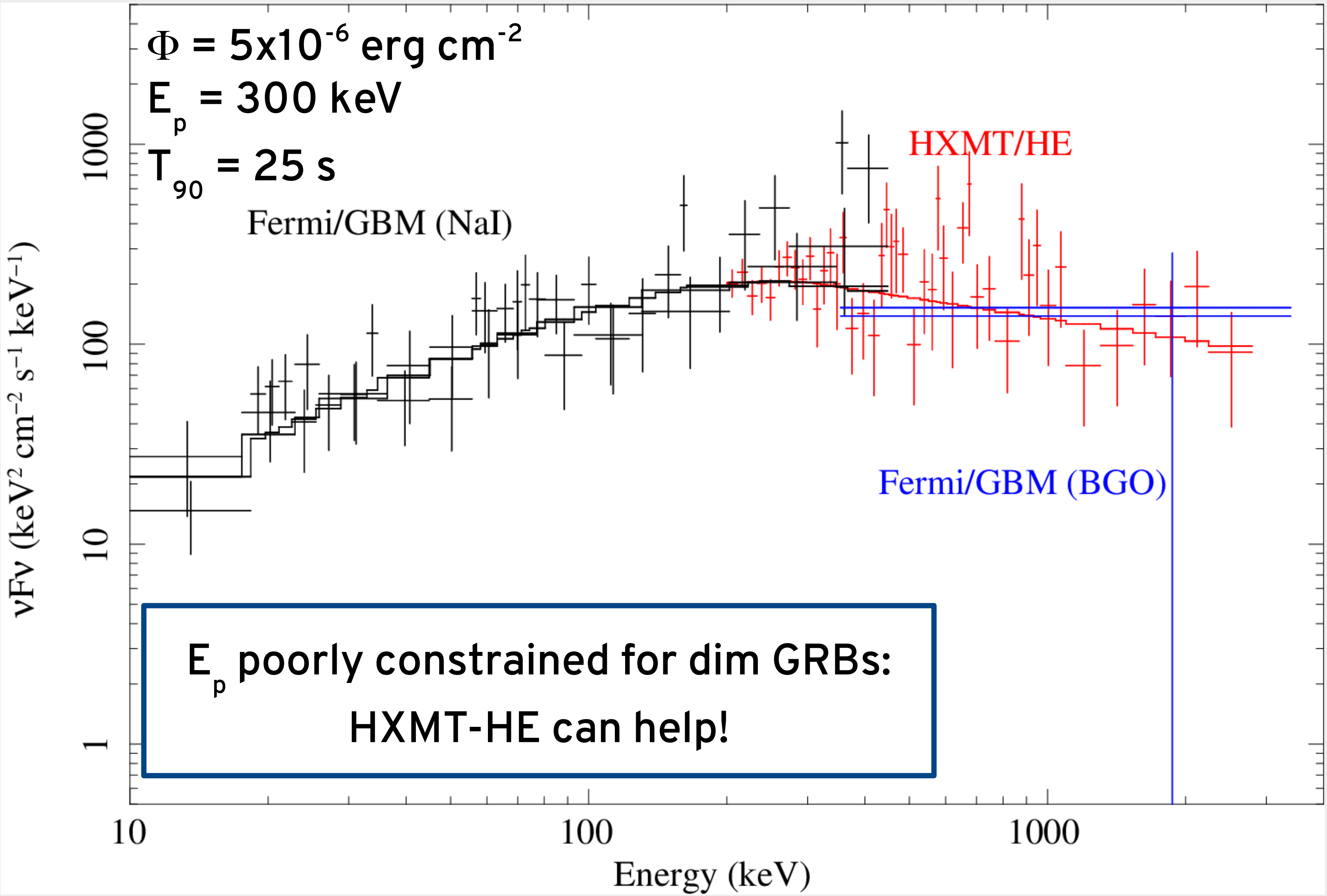
(Kindly provided to us by Shaolin Xiong on Feb 2017)

Results:
joint spectral analysis

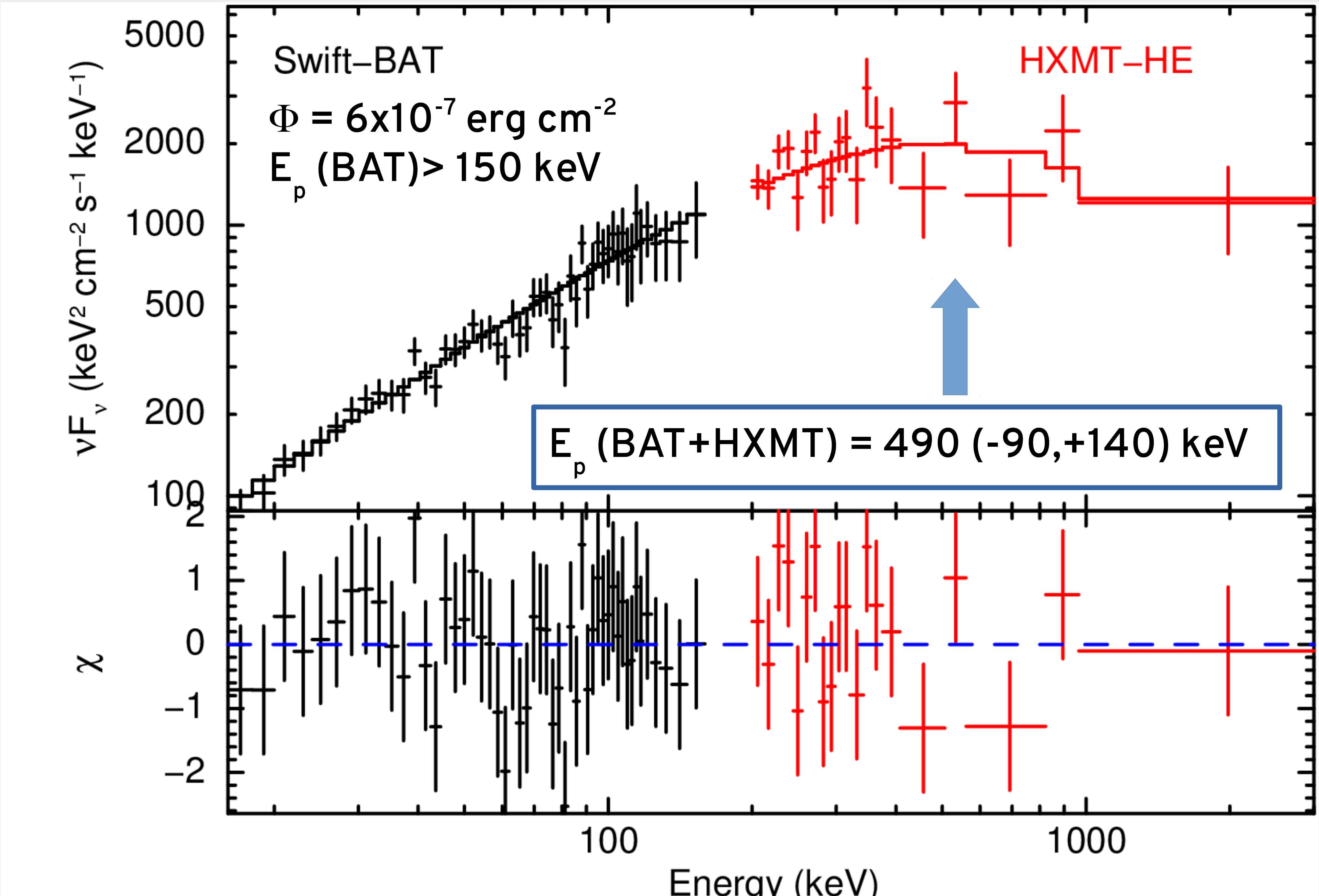
Swift-BAT + HXMT-HE



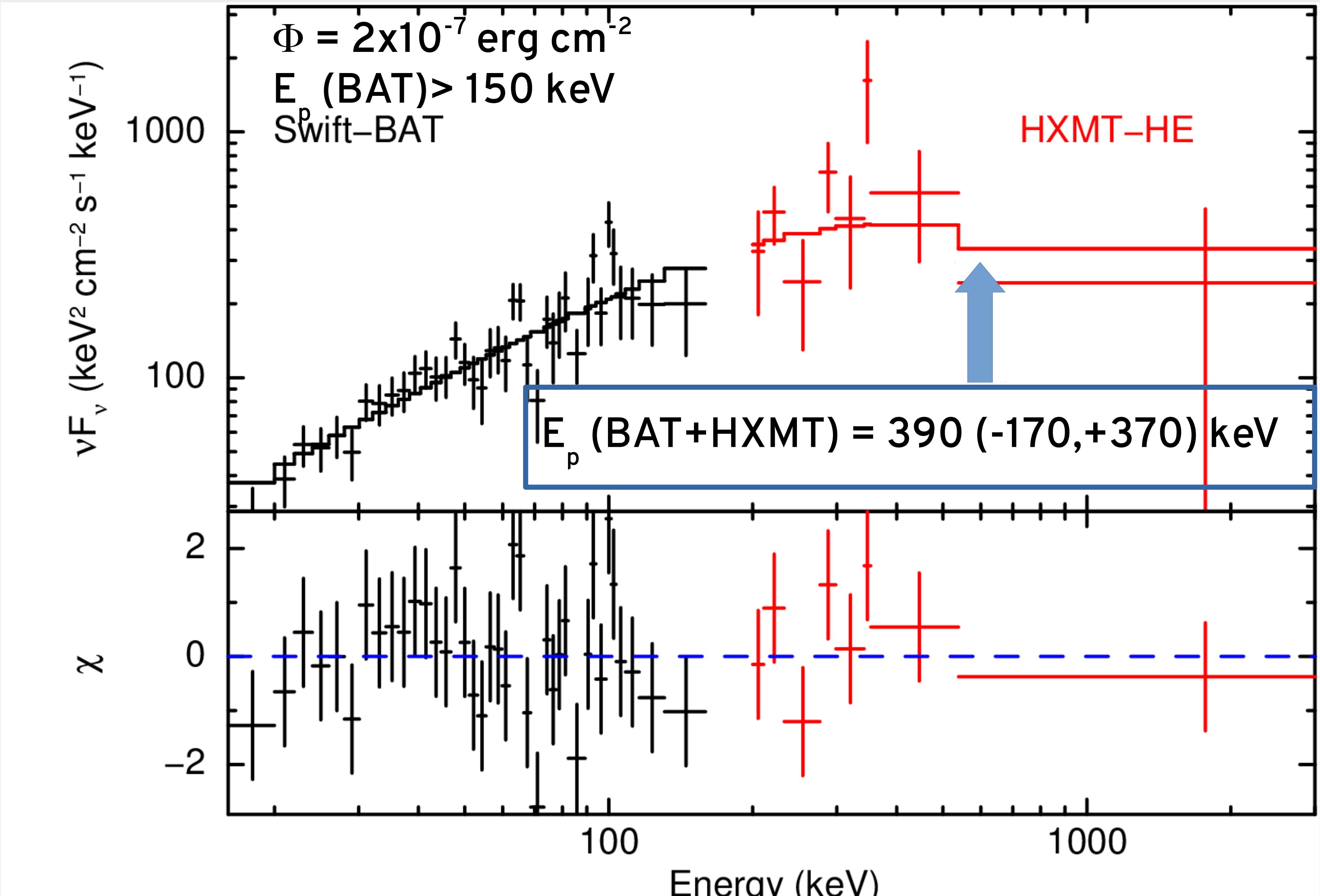
Fermi-GBM + HXMT-HE: dim long GRB



Bright Swift-BAT short 130603B



Mid-fluence Swift-BAT short 100625A



Results:
temporal analysis

Pulse asymmetry/width paradigm

Norris+(2000)

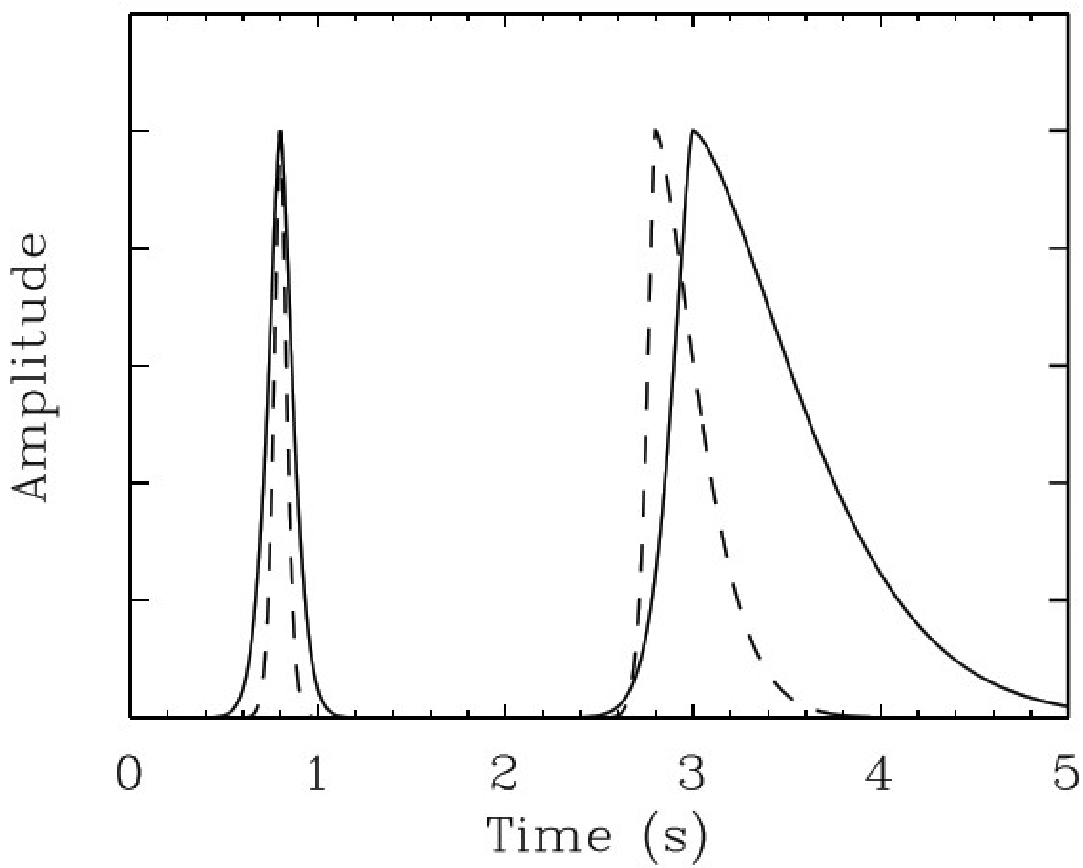


FIG. 1.—Pulse asymmetry/energy-shift paradigm. *Solid lines*: low-energy (few times 10 keV); *dashed lines*: high-energy (few times 100 keV) emission. Pulse shapes range from narrow and symmetric with negligible centroid shift with energy to wide and asymmetric with centroid shift comparable to full width at half-maximum. See Norris et al. (1996).

- In almost all cases soft photons lag behind hard photons (=positive lag)
- Soft profiles are broader and more asymmetric
- Lag correlates with width (the broader the pulse, the greater the lag)

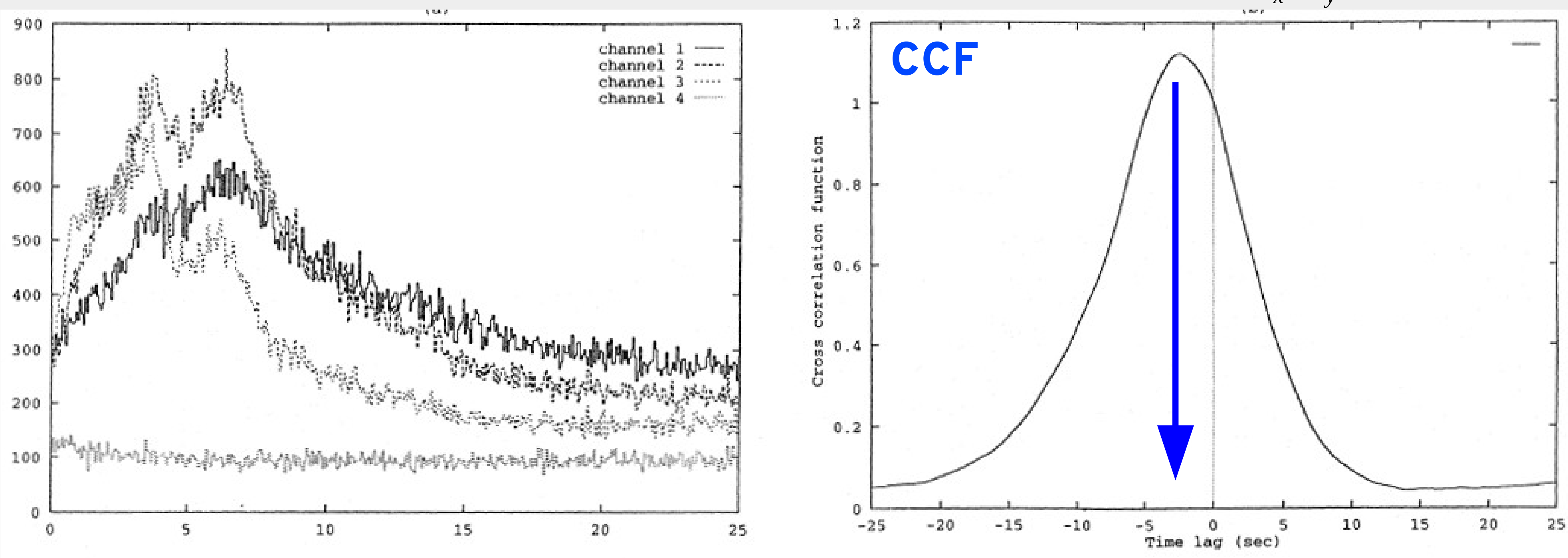
How is it measured?

- [**By cross-correlating the two profiles and taking the peak of the cross-correlation function (CCF)**] — We consider this (most used)

- By fitting the peaks and measuring the delay between them.

They may differ insomuch as the profiles' shapes are different!

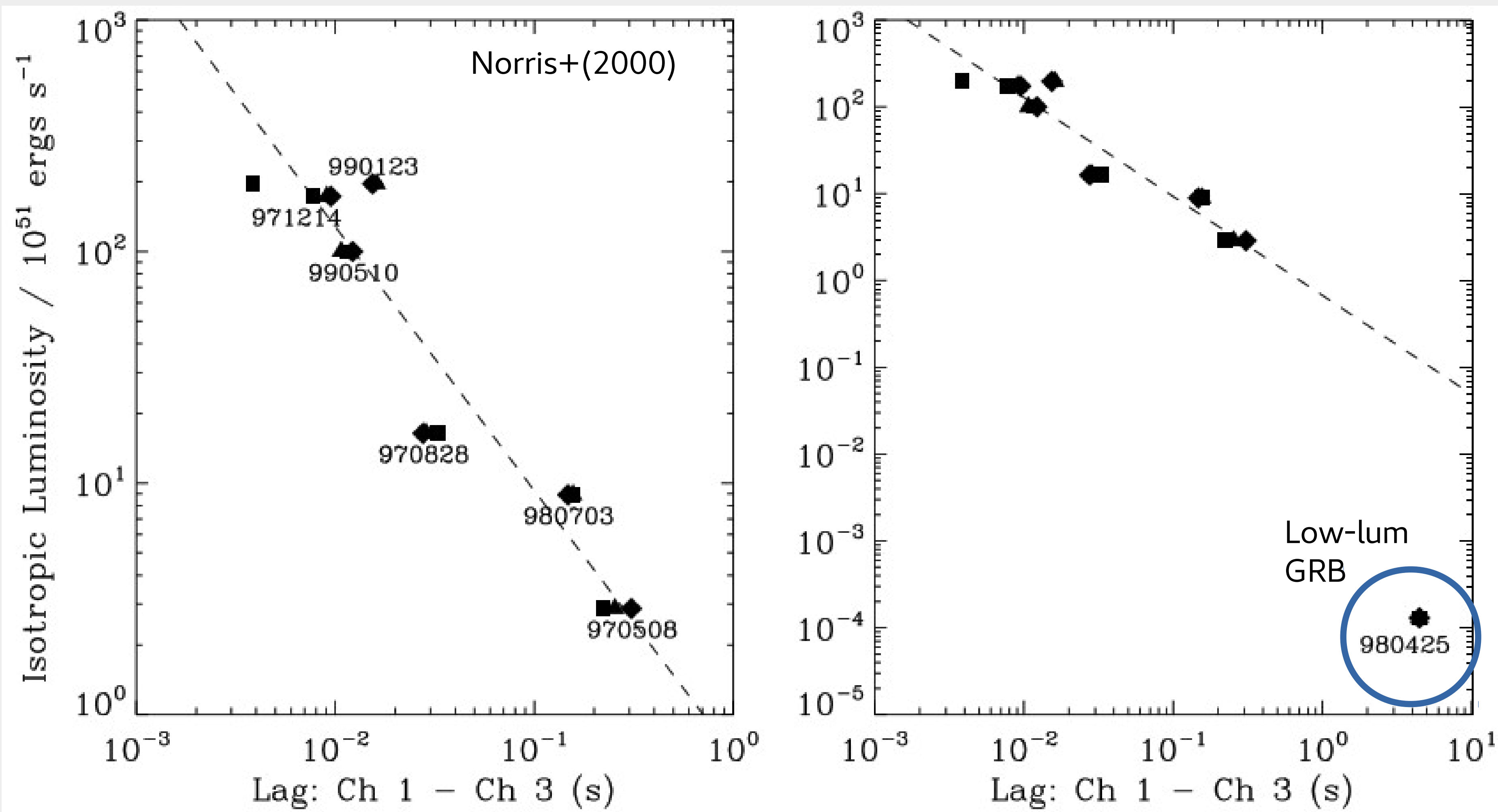
$$\mathrm{CCF}(\tau_i) \equiv \frac{(1/N)\sum_{j=0}^{N-1}(x_j-\bar{x})\,(y_{(i+j)\bmod N}-\bar{y})}{\sigma_x\,\sigma_y}$$



Cheng+(1995)

Why do we care about lags?

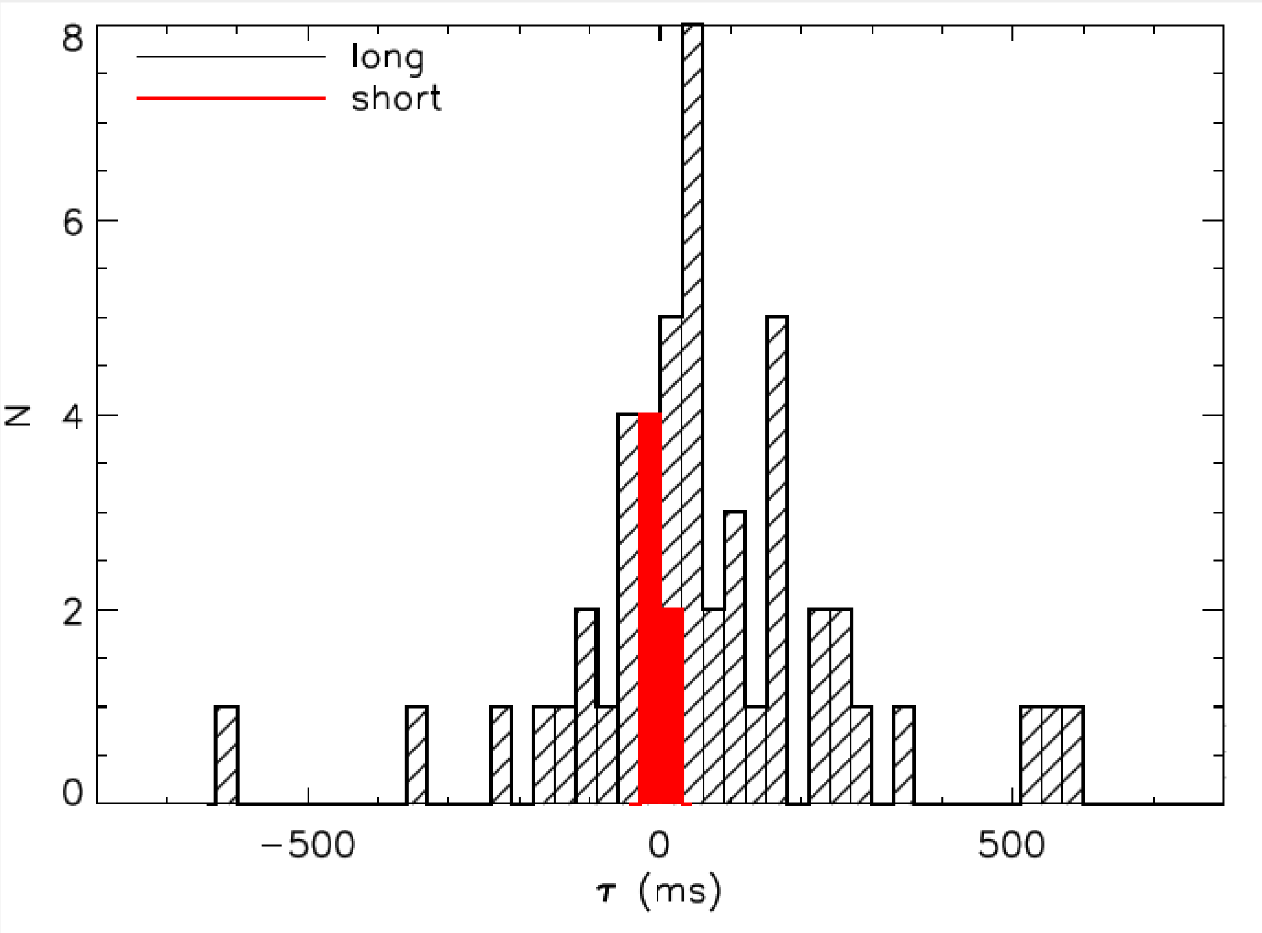
- Lag τ- luminosity L correlation ($L \propto \tau^{-1}$) for long GRBs
- Empirical way of classifying short vs. long GRB (for ambiguous cases)
- While physical relevant, there's no exhaustive self-consistent explanation



Pre-Swift GRBs (BATSE data): Ch1(**25-50 keV**) vs. Ch3(**100-300 keV**)

Why do we care about lags?

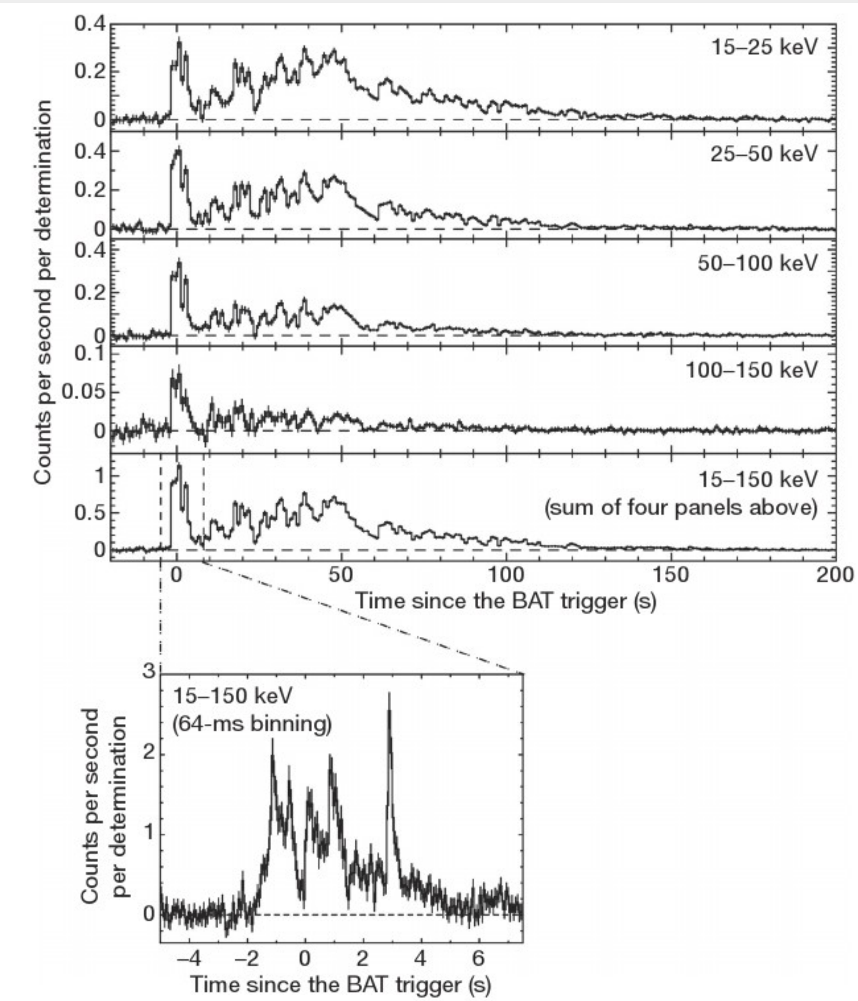
- Lag τ- luminosity L correlation ($L \propto \tau^{-1}$) for long GRBs
- Empirical way of classifying short vs. long GRB (for ambiguous cases)
- While physical relevant, there's no exhaustive self-consistent explanation

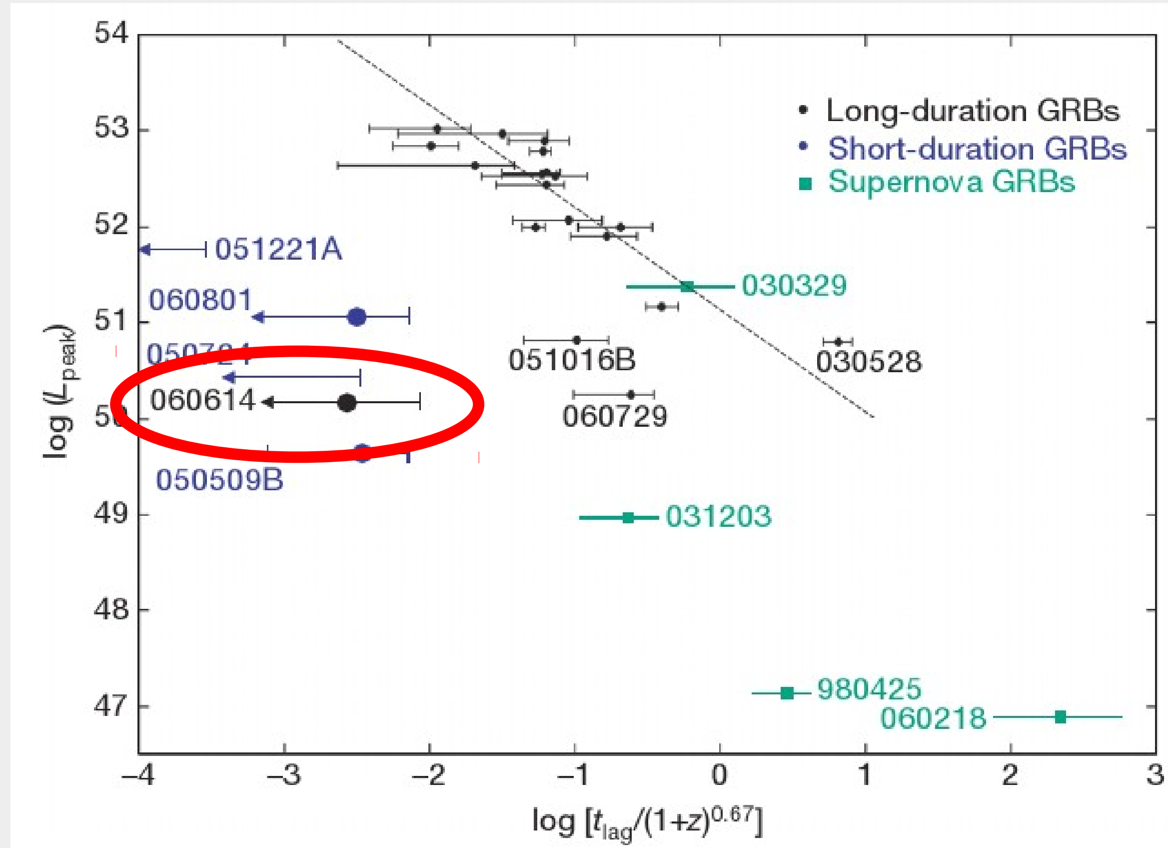


Bernardini+(2015)

Typical short GRBs display much smaller/negligible lags (within a few 10 ms)

Lag can help classify ambiguous cases such as elusive GRB 060614





Gehrels+ (2006)

The added value of Insight-HXMT

- Limitations up to now:
  - CCF needs lots of counts in both channels
    - at > 300 keV almost uncharted territory in the lag calculation
    - Short GRBs are particularly hampered (fewer counts and spectrally harder than LGRBs)

The unrivalled effective area above 300 keV of Insight-HXMT holds a great promise

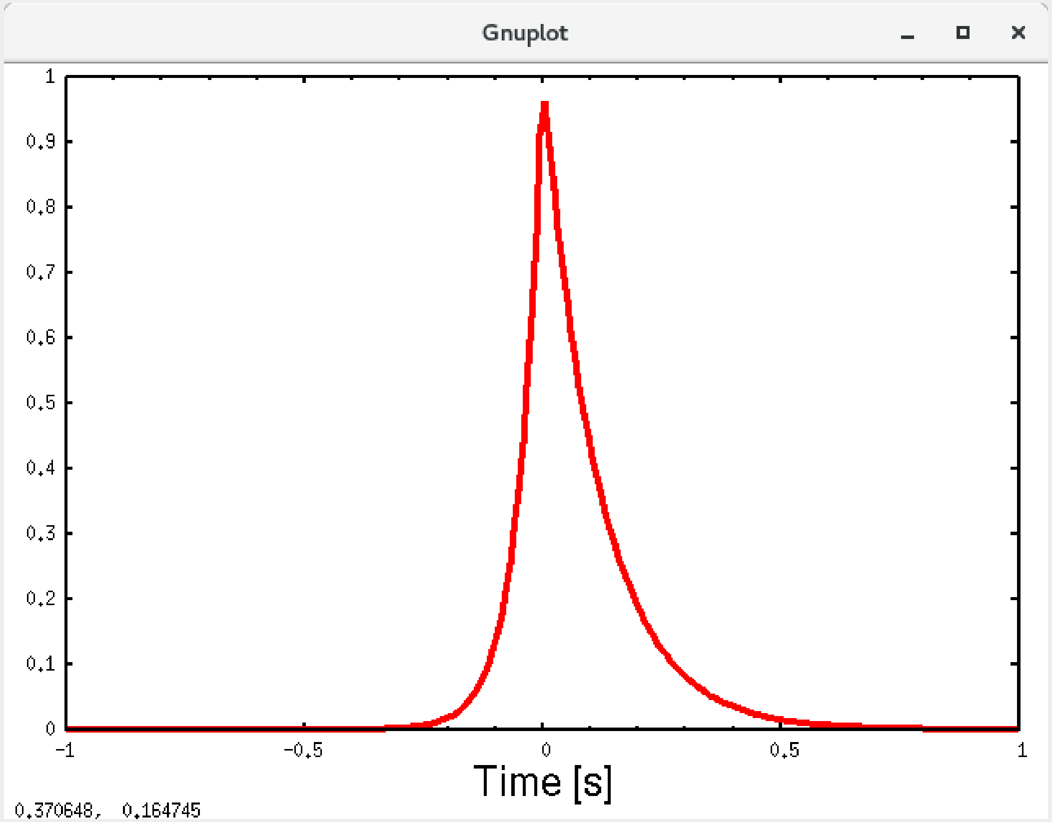
Short GRB simulated profiles and corresponding CCF-estimated lags

FRED: simple exp model

$$f(t) \equiv \begin{cases} A \;\; e^{t/t_r} & (t<0) \\ A \;\; e^{-t/t_d} & (t>0) \end{cases}$$

$$t_d/t_r \sim 2 \div 3$$

Time interval between f1 and f2 cumulative fluence:



$$T(f_1, f_2) = -t_r \ln\left[f_1\left(1+\frac{t_d}{t_r}\right)\right] - t_d \ln\left[1+\frac{t_r}{t_d} - f_2\left(1+\frac{t_r}{t_d}\right)\right]$$

$$T_{90} = T(0.05, 0.95)$$

Assumed hard-to-soft evolution

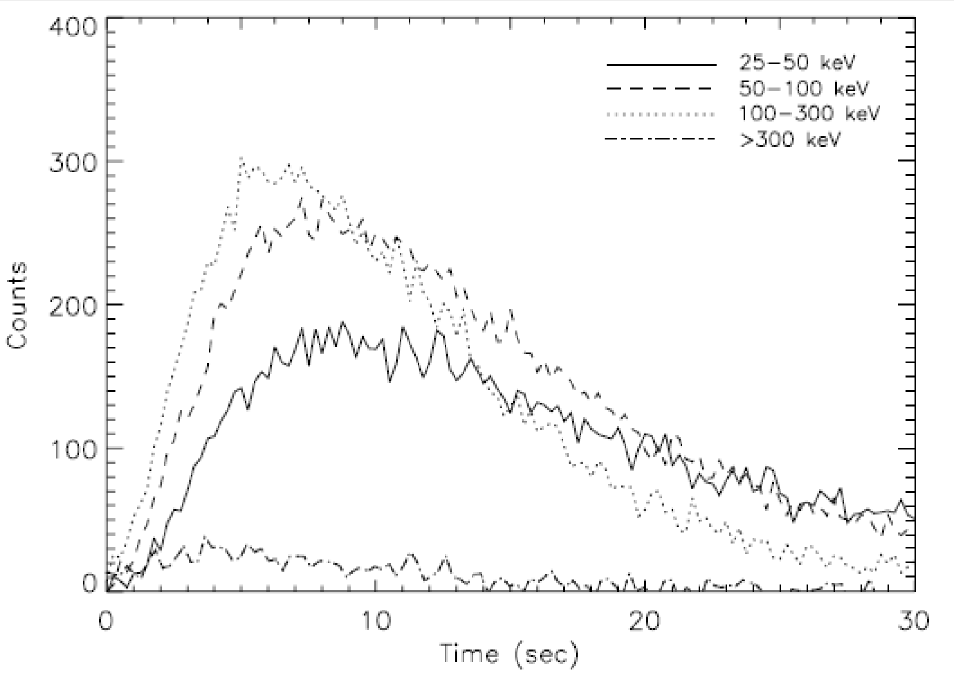
Band function :

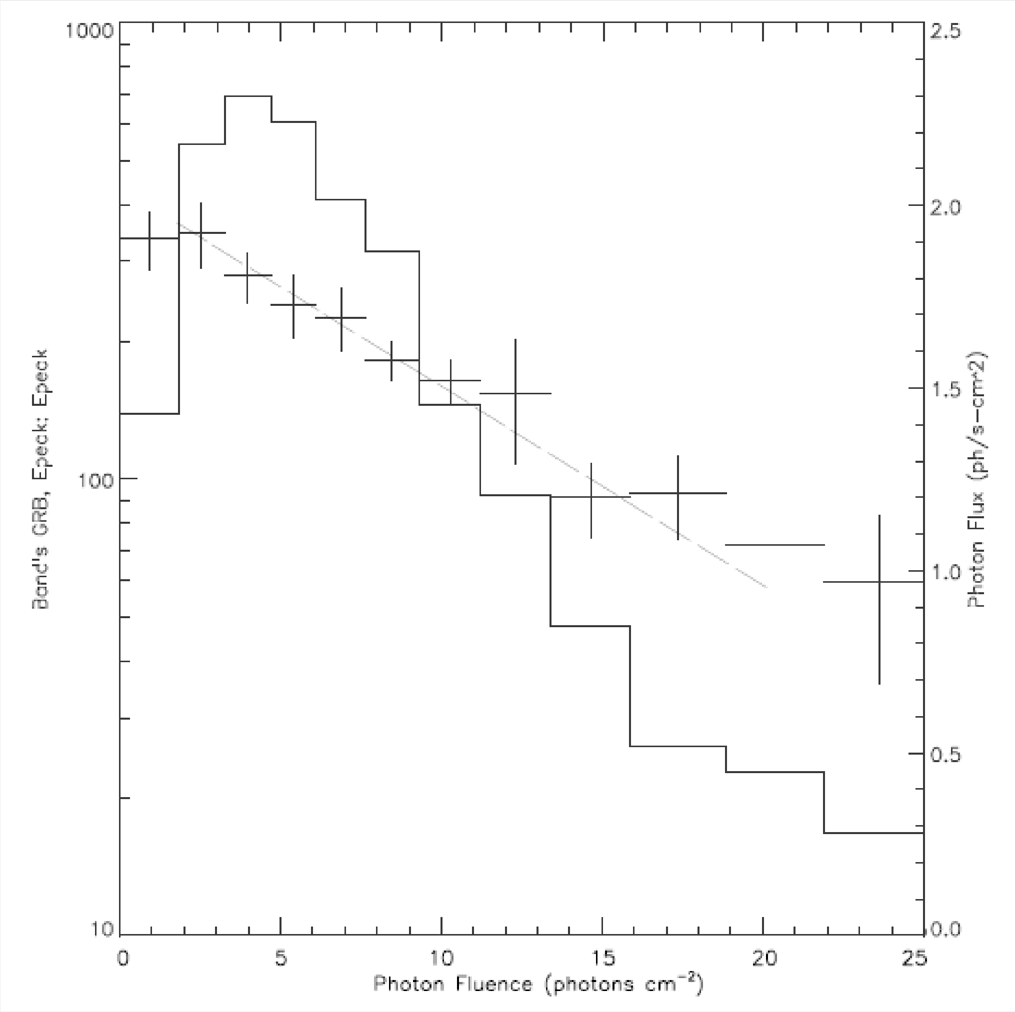
$\alpha_B = -0.5$

$\beta_B = -2.3$

$E_{p,0} = 1 \ \mathrm{MeV}$

$$E_p(t) = E_{p,0}\left(1 + \frac{t + 6t_r}{6(t_r + t_d)}\right)^{-2}$$





Kocevski & Liang (2003)

Simulated short GRBs (single-FRED shaped)

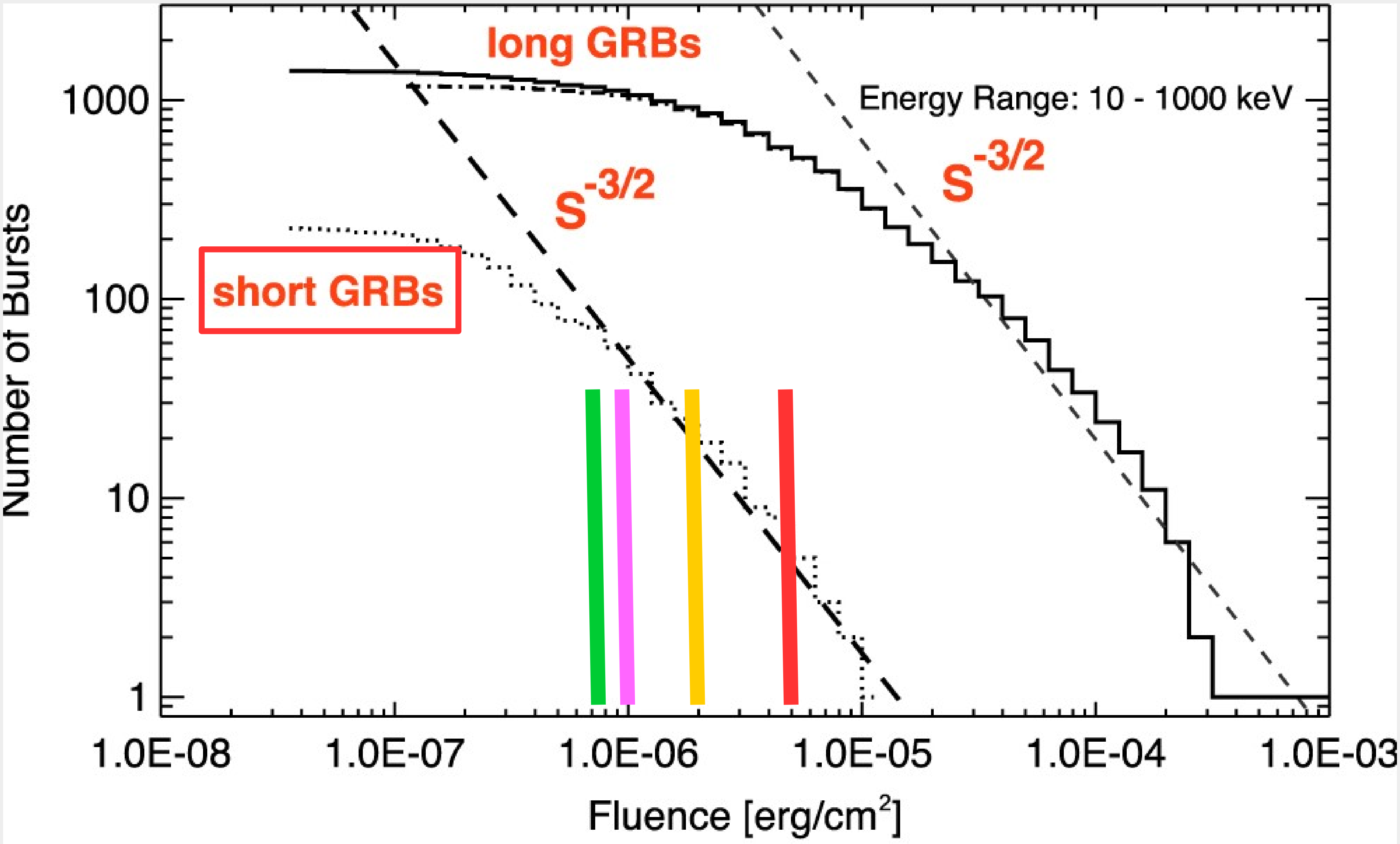
Fluence[cgs] T90 [s]	8e-7	1e-6	2e-6	5e-6
0.84 (tr=0.1s, td=0.25 s)	worst S/N			
0.40 (tr=0.05s, td=0.12 s)				best S/N

⟶ = improving S/N

Fluence are in the 10-1000 keV (Fermi-GBM band)

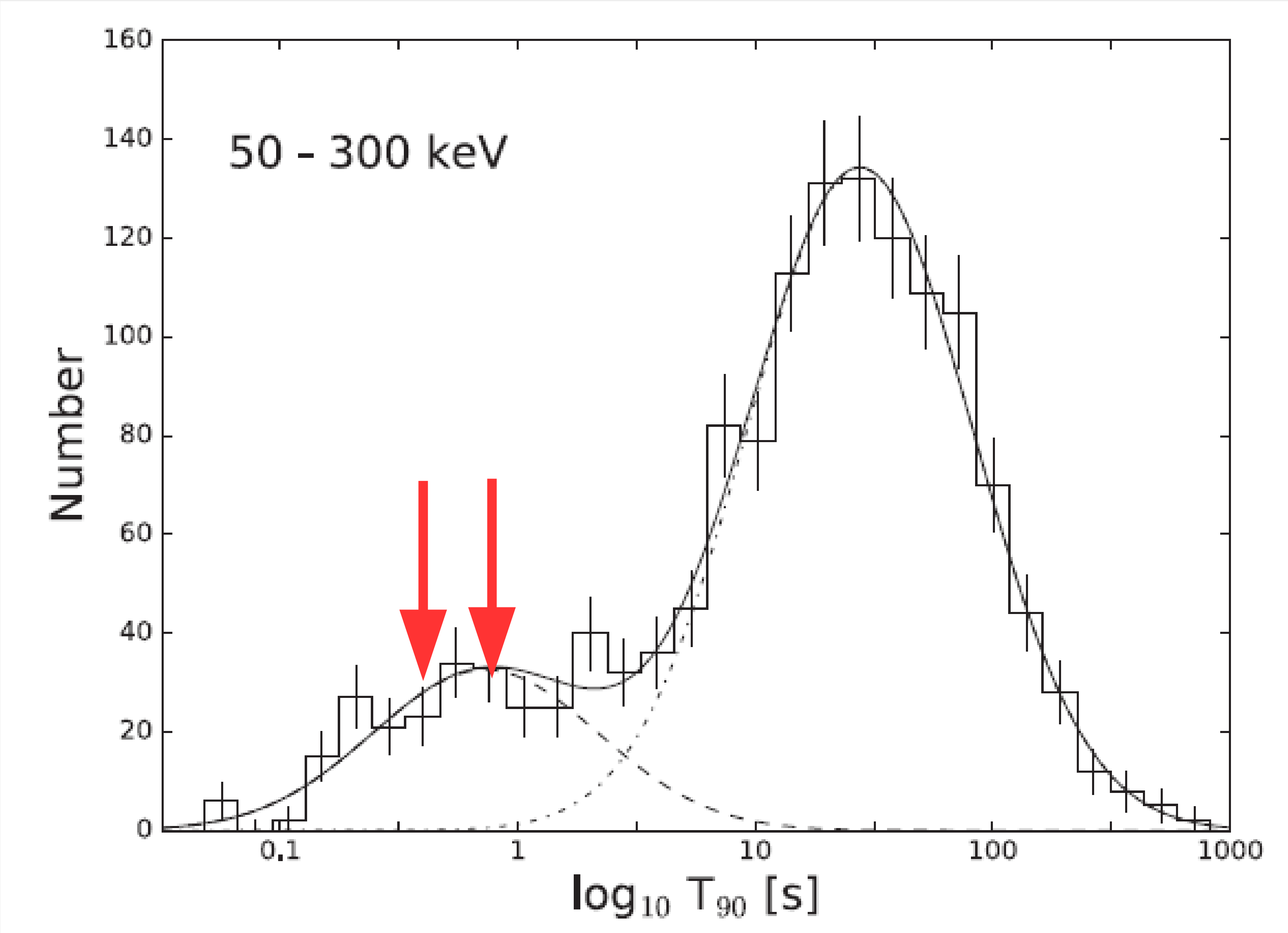
HXMT background rate: ~6000 cts/s

Mid/bright Fermi/GBM fluence distribution tail



Fermi/GBM catalogue (Bhat+16)

Short GRB Fermi/GBM T_{90} distribution



Fermi/GBM catalogue (Bhat+16)

Simulations in a nutshell

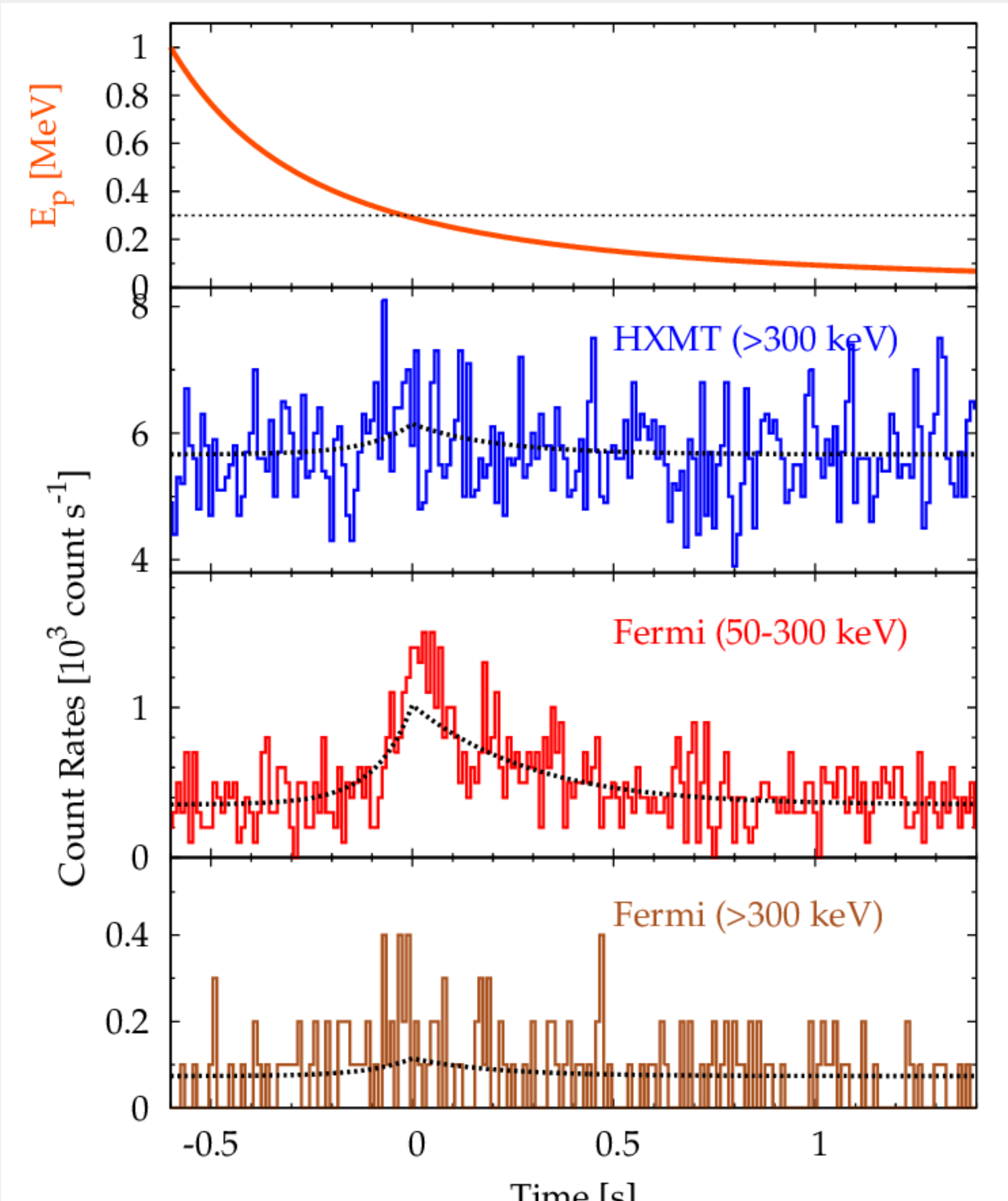
- Energy bands:
  - Fermi/GBM: **50 – 300 keV**
  - HXMT (GRB mode): **> 300 keV**

- Min time binning: 10 ms (we binned up as imposed by S/N)

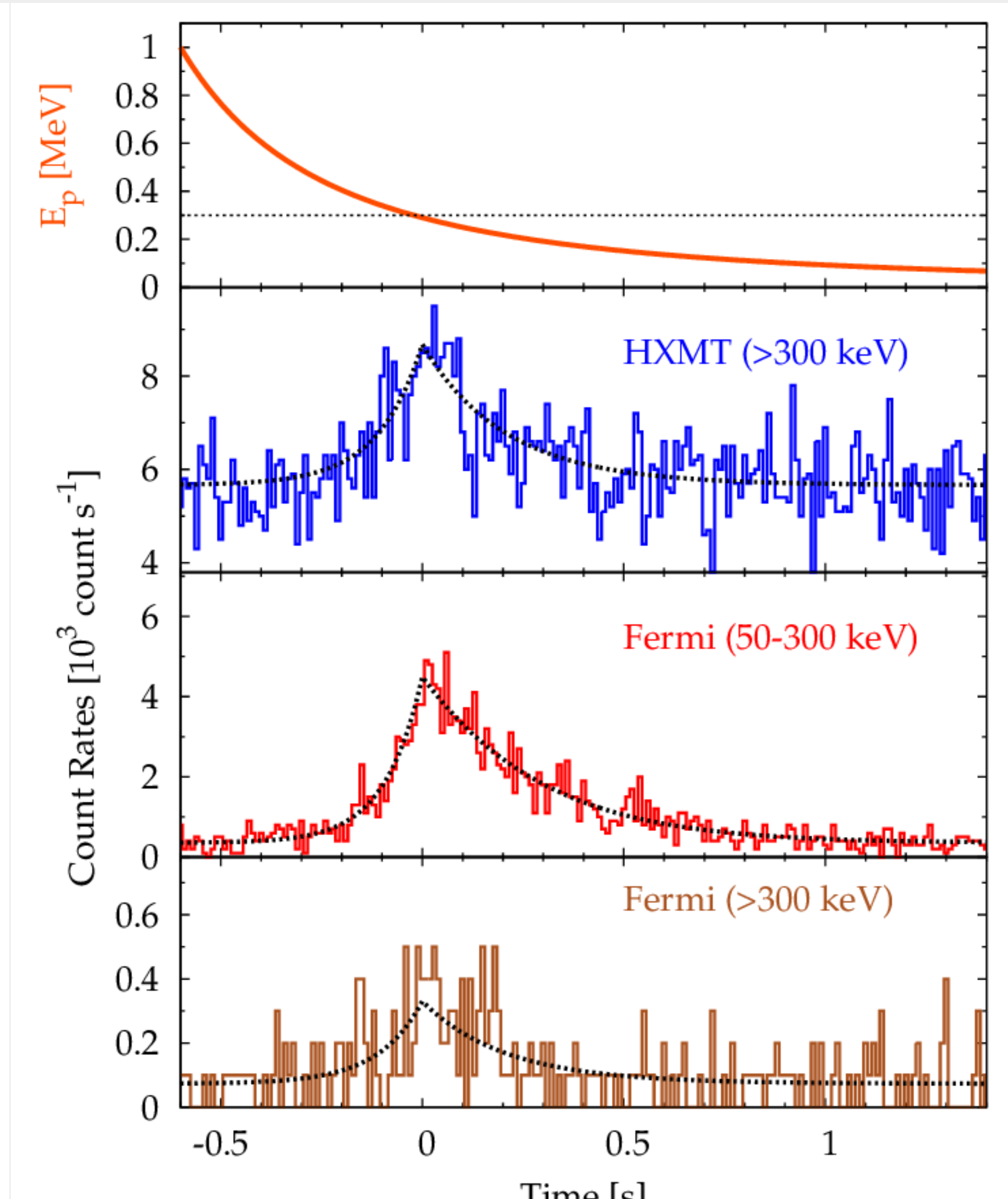
- For each combination of (pulse duration, fluence):
  - Simulate 1 GBM (50-300 keV) and 1 HXMT (>300 keV) profile
  - Calculate true (=without stat noise) lag
  - Simulated profiles are added Poisson noise (including bkg)
  - Each profile is smoothed with a Savitzky-Golyay filter (to avoid extra variance due to 2nd-order realisations) and used to generate 1000 fake profiles for each instrument
  - 1000 CCF are fitted with a cubic and the resulting lag distribution yields the best lag along with 1, 2 sigma (Gaussian) uncertainties.

Simulated pulse1 (T_{90}=0.84 s)

F=8e-7 cgs

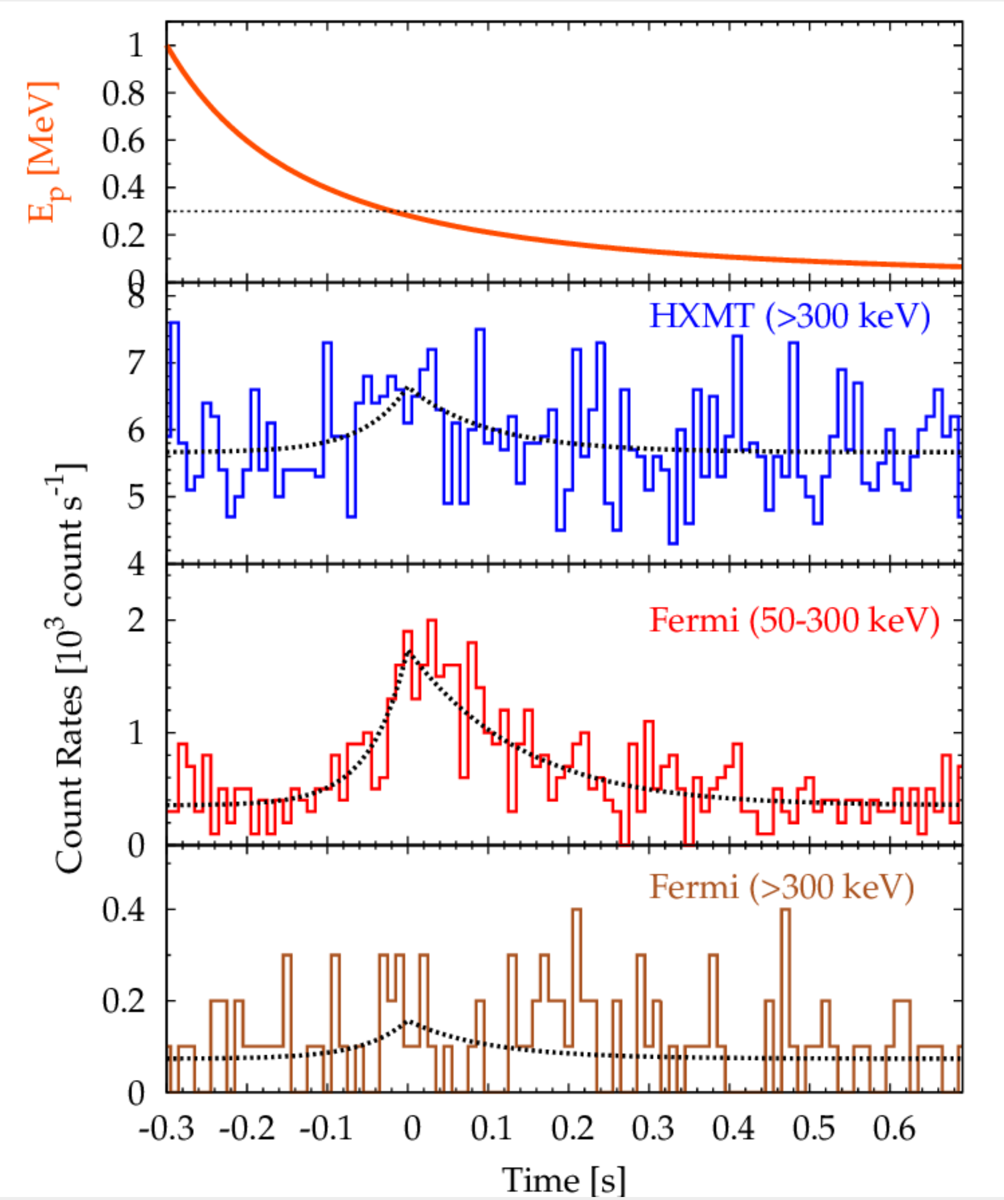


F=5e-6 cgs

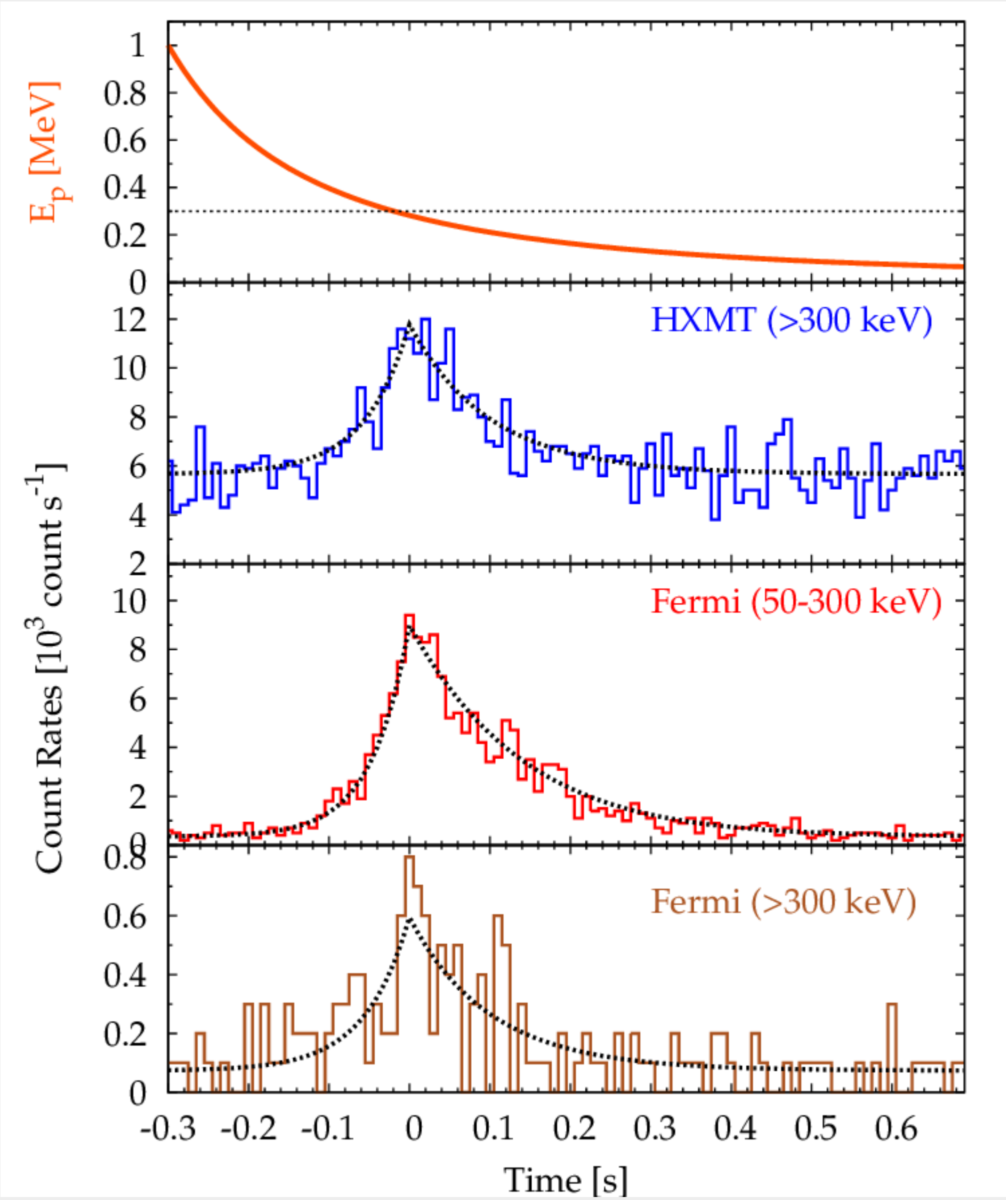


Simulated pulse2 (T_{90}=0.40 s)

F=8e-7 cgs



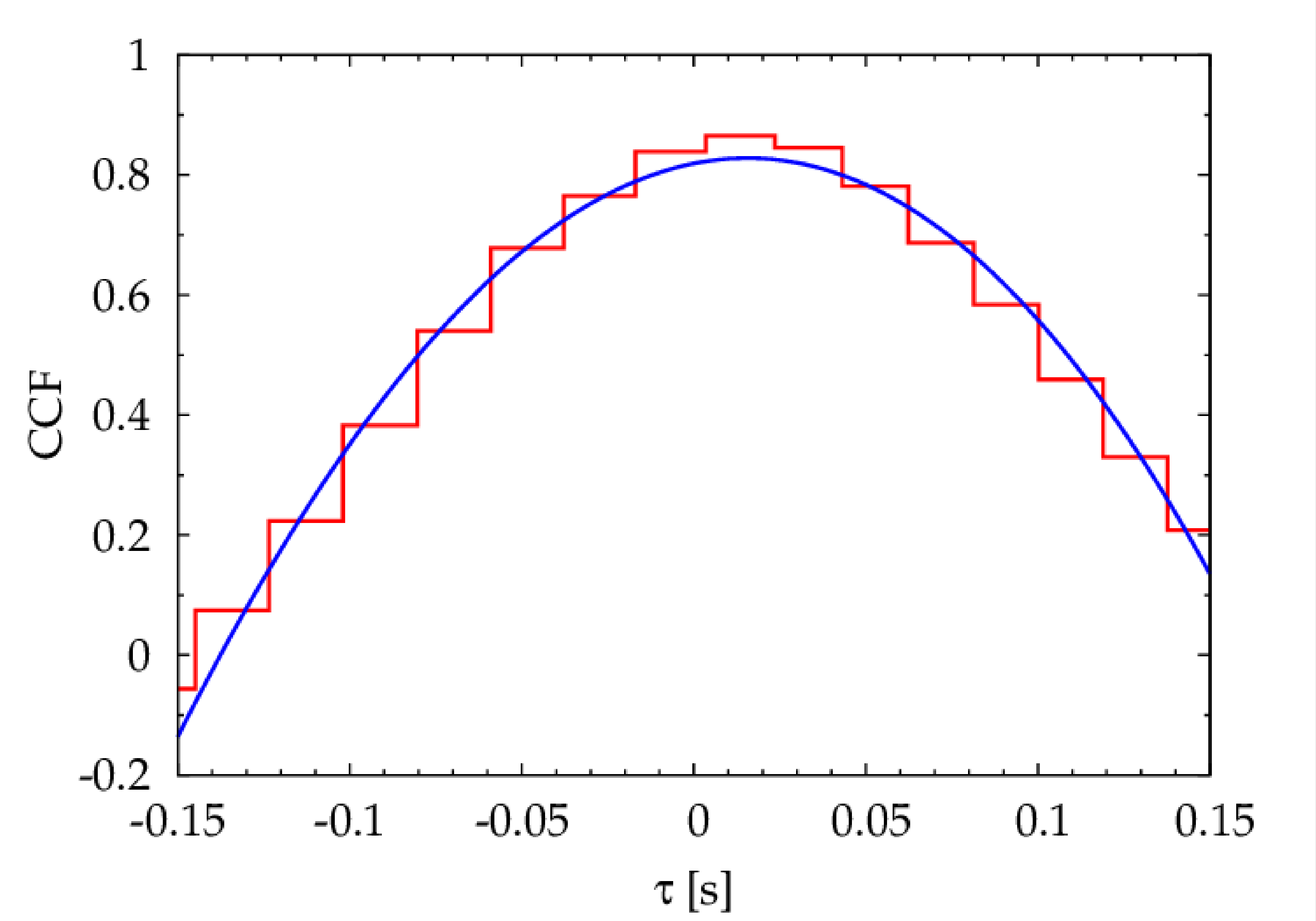
F=5e-6 cgs



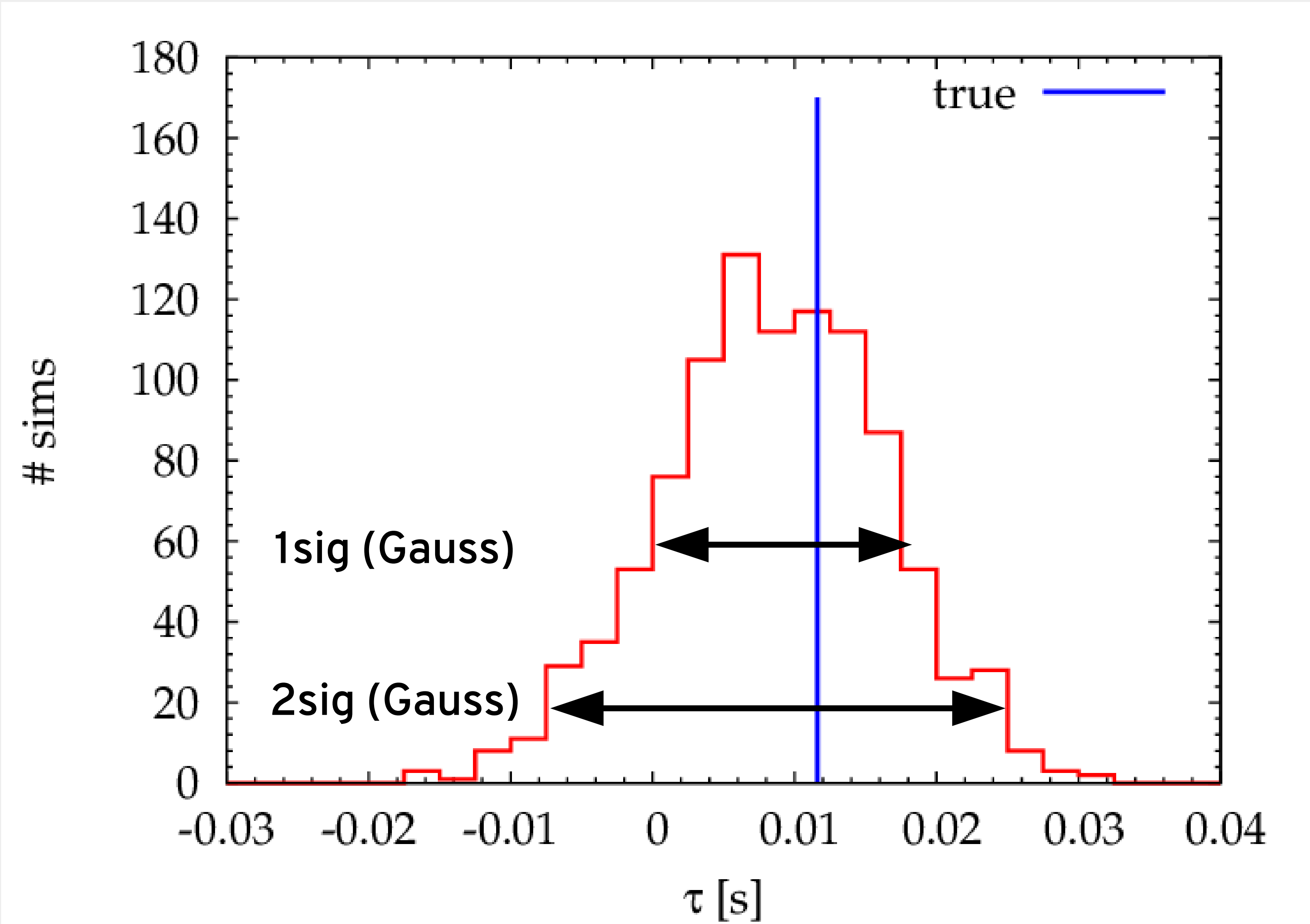
Results: Fermi/GBM vs. HXMT CCF

Example of CCF of simulated profiles

Best fitting cubic (F=5e-6 cgs, T_{90}=0.40 s)

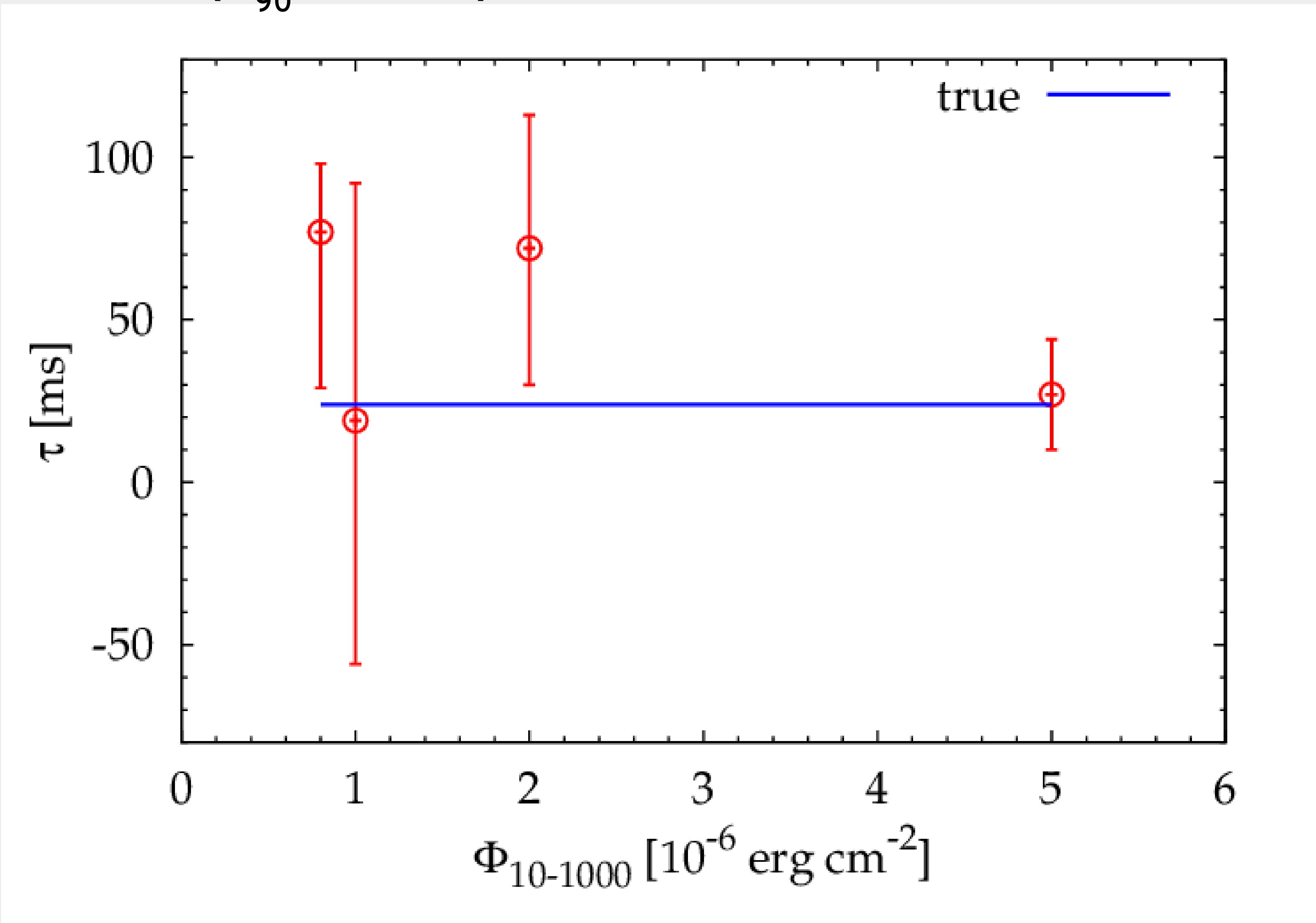


Lag distribution (for a given set of simulated CCF)



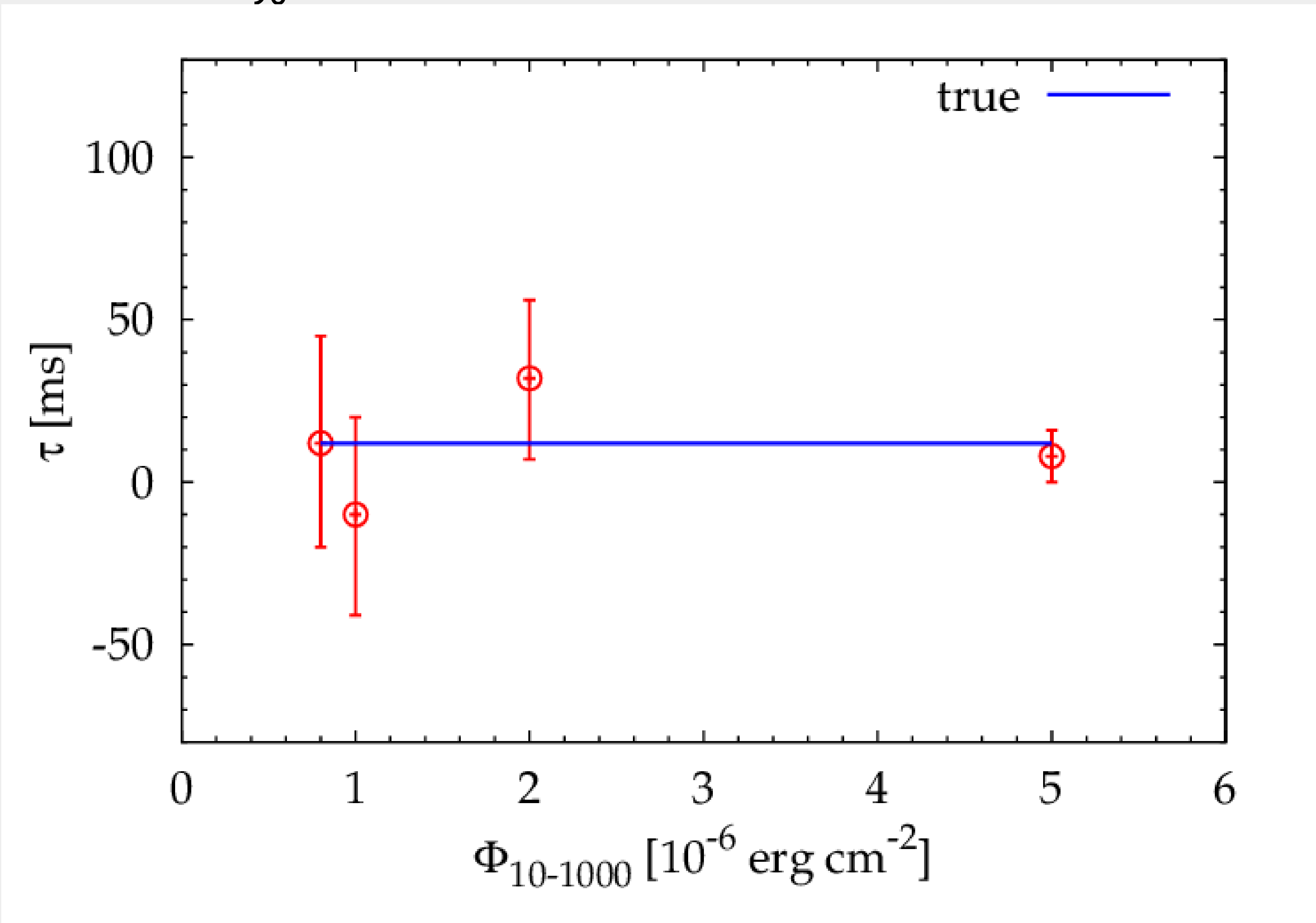
Estimated & true lag vs. fluence

Pulse 1 (T_{90}=0.84 s)



Estimated & true lag vs. fluence

Pulse 2 (T_{90}=0.40 s)



Conclusions

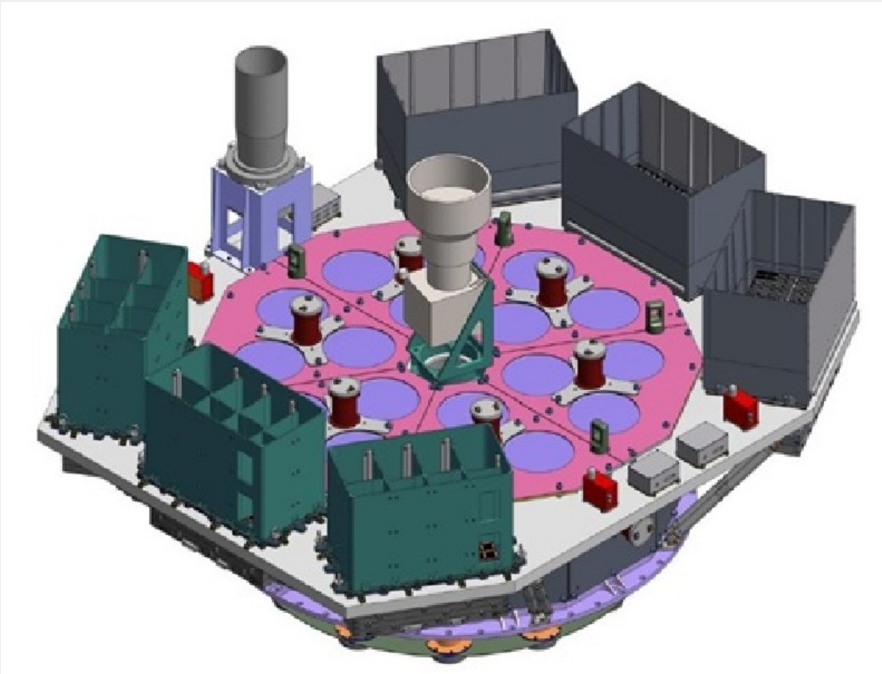
- Joint analysis of HXMT-HE (GRB mode) with either Swift-BAT or Fermi-GBM will greatly improve constraining Ep and high-energy index for long GRBs. Gain insights into:
  - GRB physics (still don't know what makes gamma-rays)
  - GRB as cosmological probes through Ep-Eiso (Amati) relation

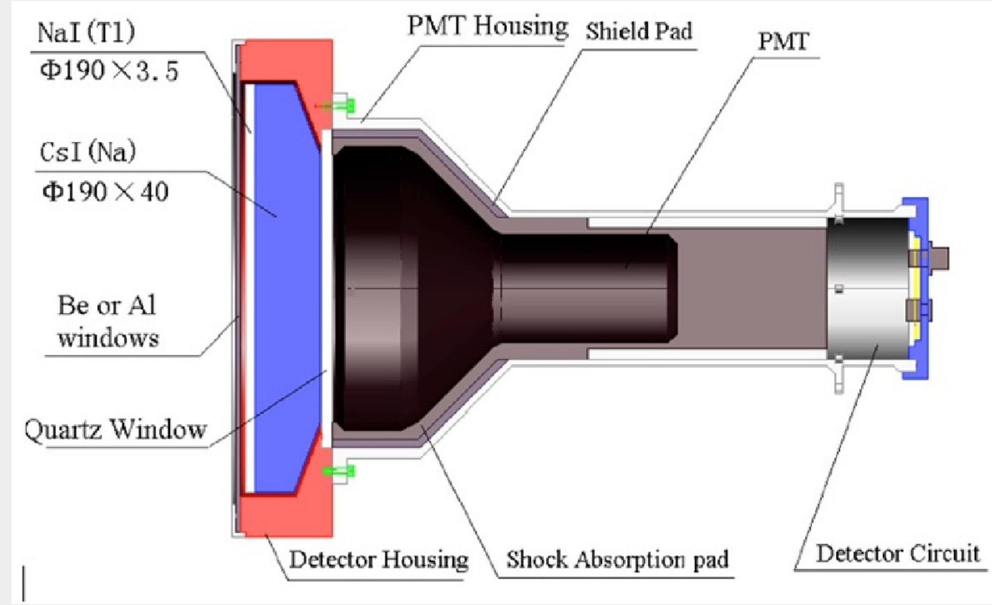
- Joint analysis of short (hard) GRBs:
  - Help characterize and possibly find different classes (soft SGRBs, such as GRB170817A associated to GW170817)
  - invaluable probes of binary NS-NS mergers coupled with gravitational waves!
- Spectral lag is a unique empirical parameter for the short vs. long (i.e., merger vs. collapsar) classification
- Its measure is challenging as it crucially demands lots of counts especially in the hard energy channels
- Insight-HXMT can fill in the current lack of lag-related studies above 300 keV

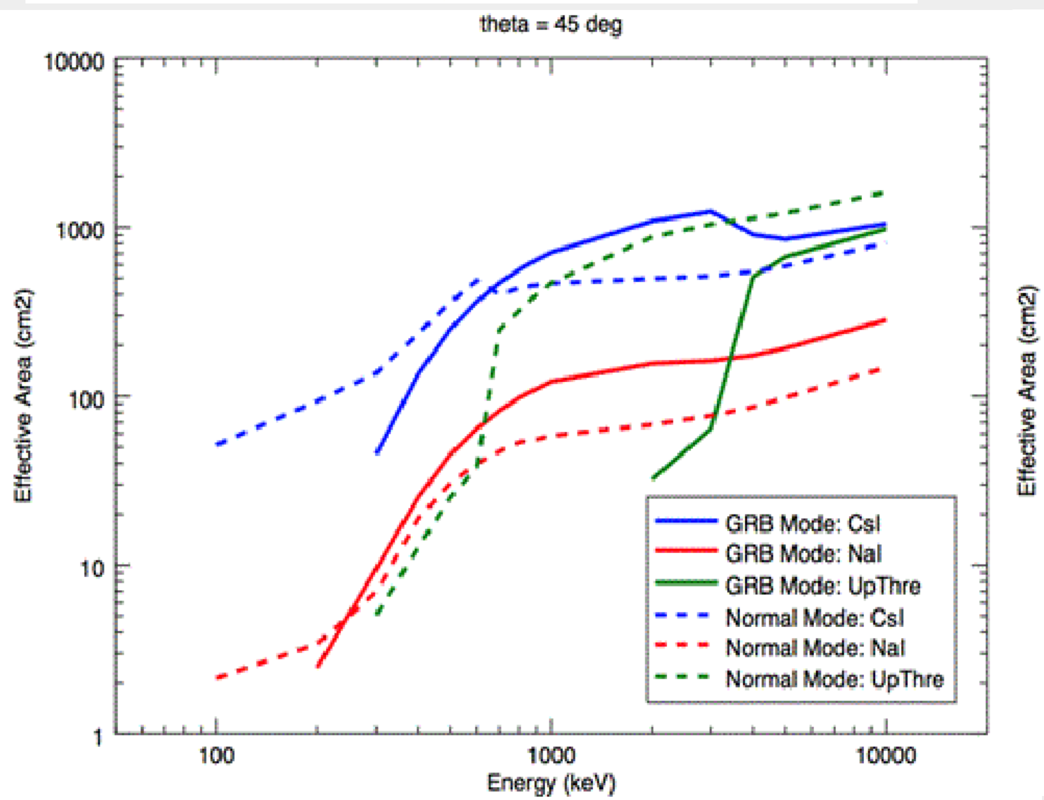
Thank you

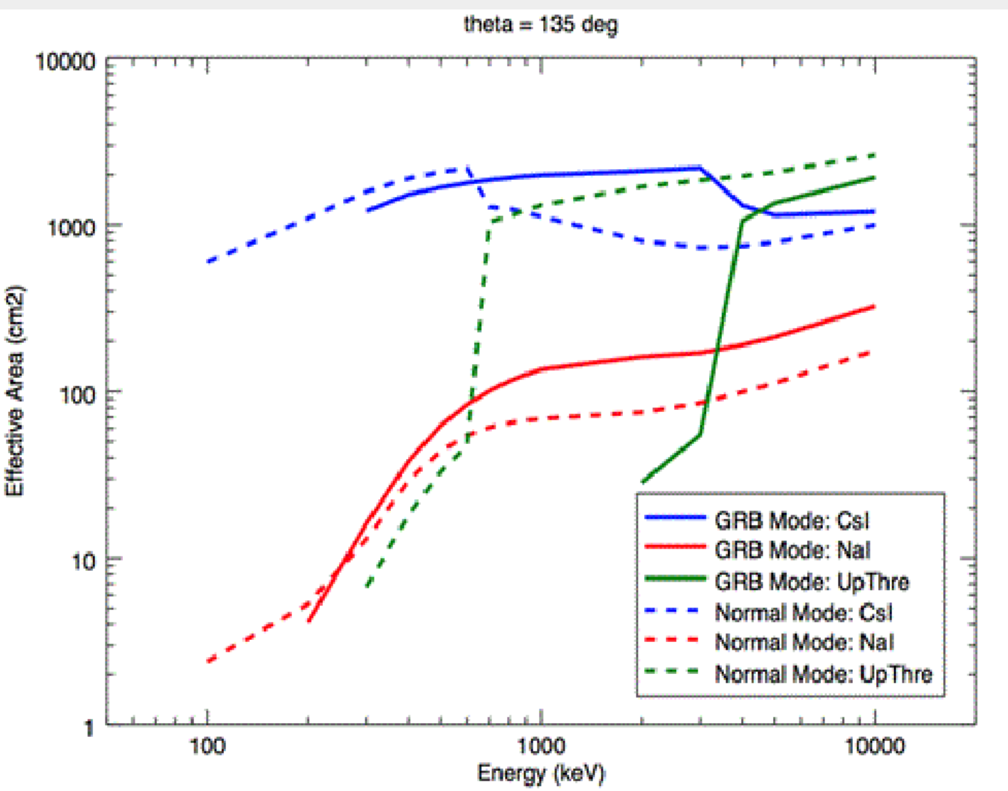
谢谢

Back-up Slides

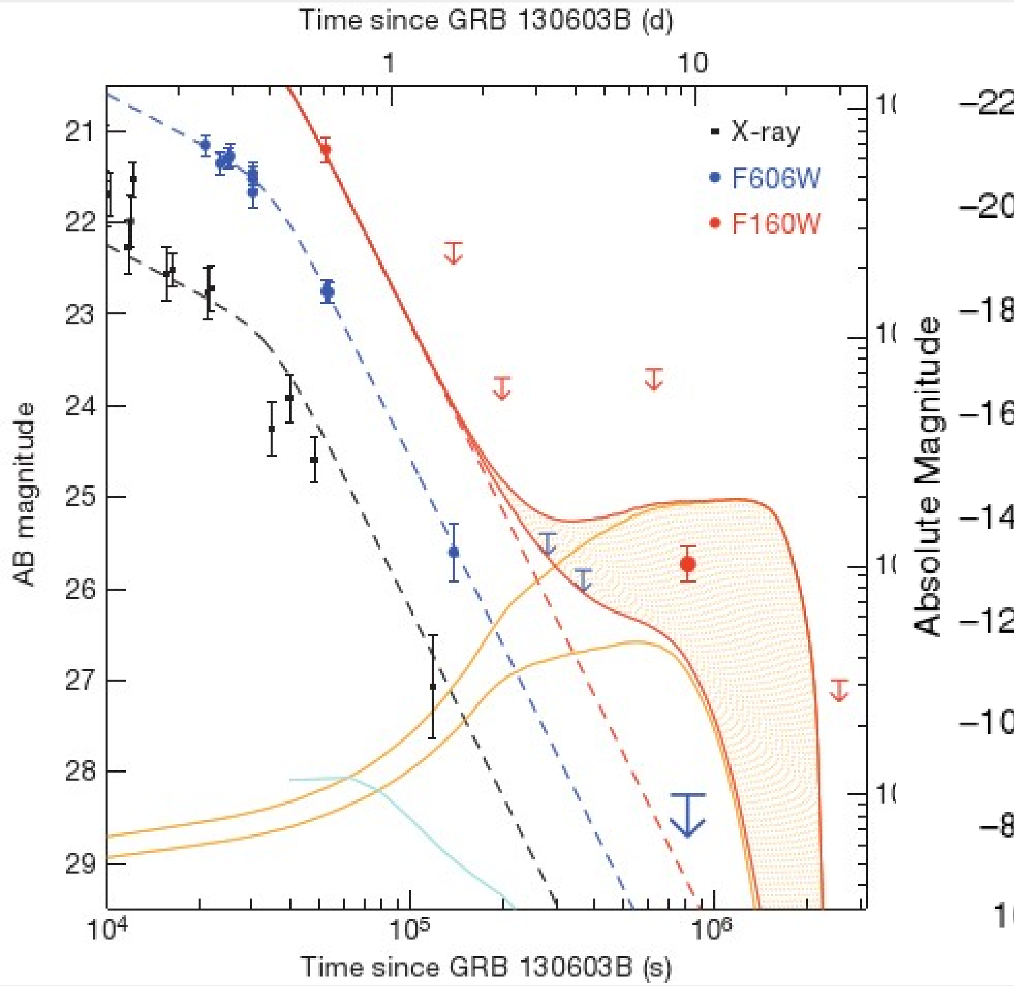



NaI (Tl)
Φ190×3.5
CsI (Na)
Φ190×40
Be or Al
windows
Quartz Window
PMT Housing
Shield Pad
PMT
Detector Housing
Shock Absorption pad
Detector Circuit

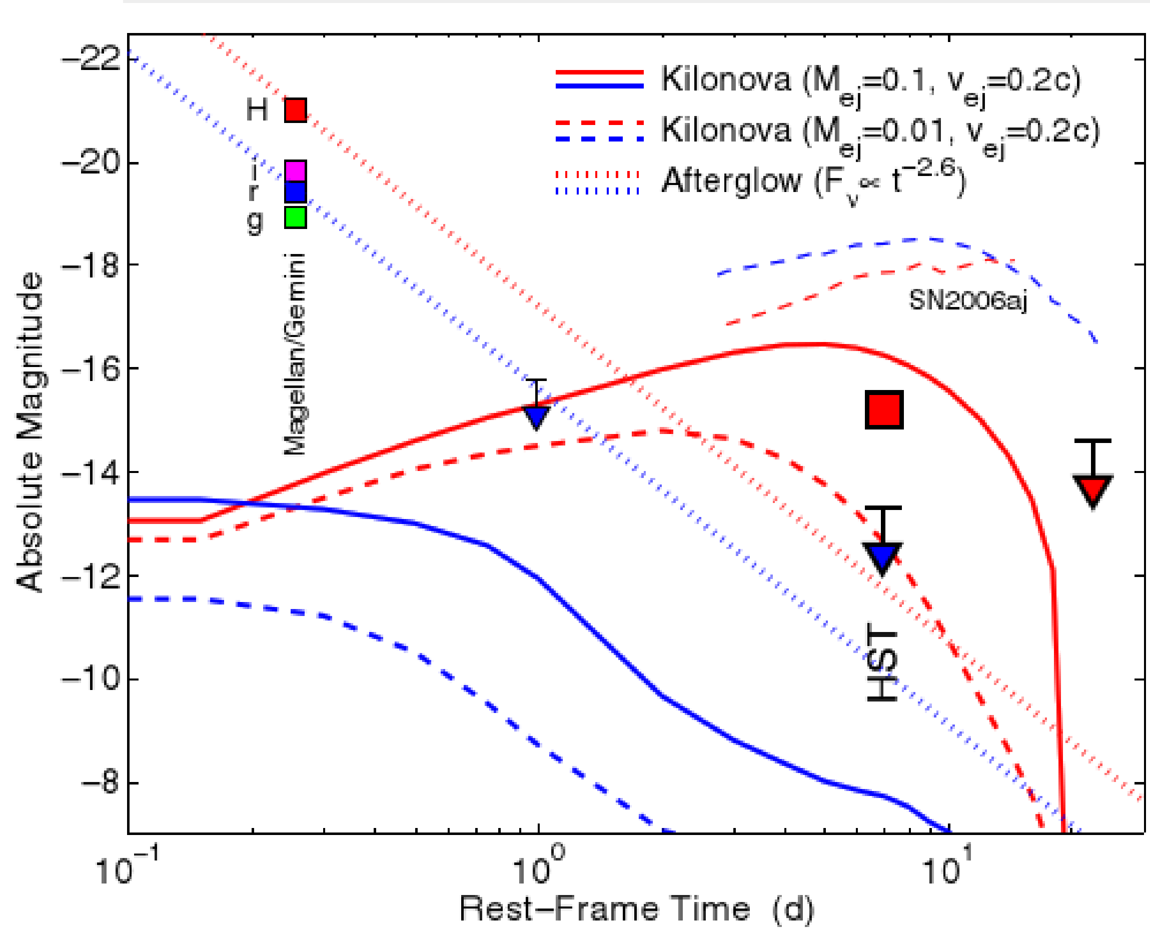

theta = 45 deg
Effective Area (cm2)
Energy (keV)
10000
1000
100
10
1
100
1000
10000
GRB Mode: CsI
GRB Mode: NaI
GRB Mode: UpThre
Normal Mode: CsI
Normal Mode: NaI
Normal Mode: UpThre


theta = 135 deg
Effective Area (cm2)
Energy (keV)
10000
1000
100
10
1
100
1000
10000
GRB Mode: CsI
GRB Mode: NaI
GRB Mode: UpThre
Normal Mode: CsI
Normal Mode: NaI
Normal Mode: UpThre

SGRB 130603B: KN evidence in afterglow

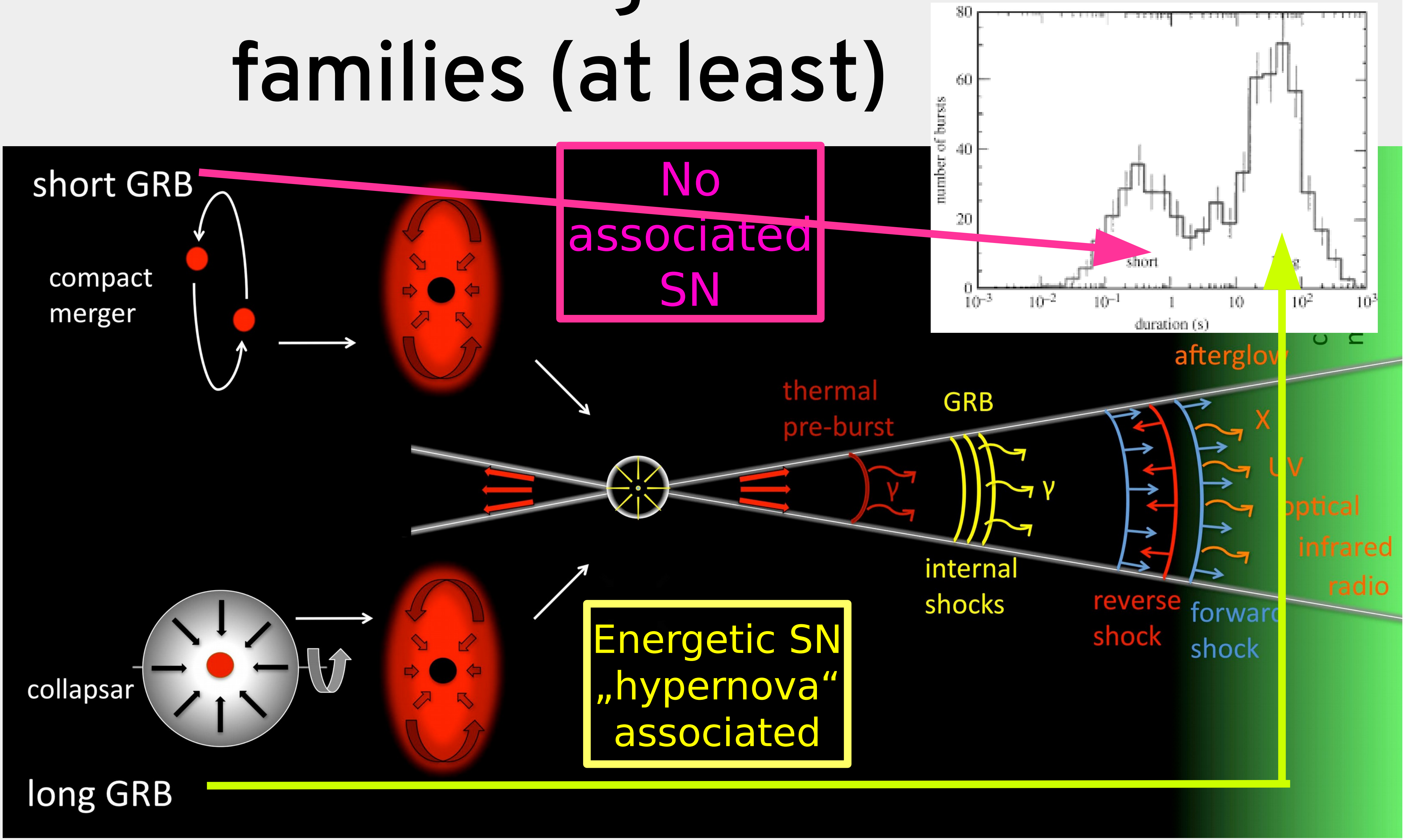


(Tanvir+13, Nat)

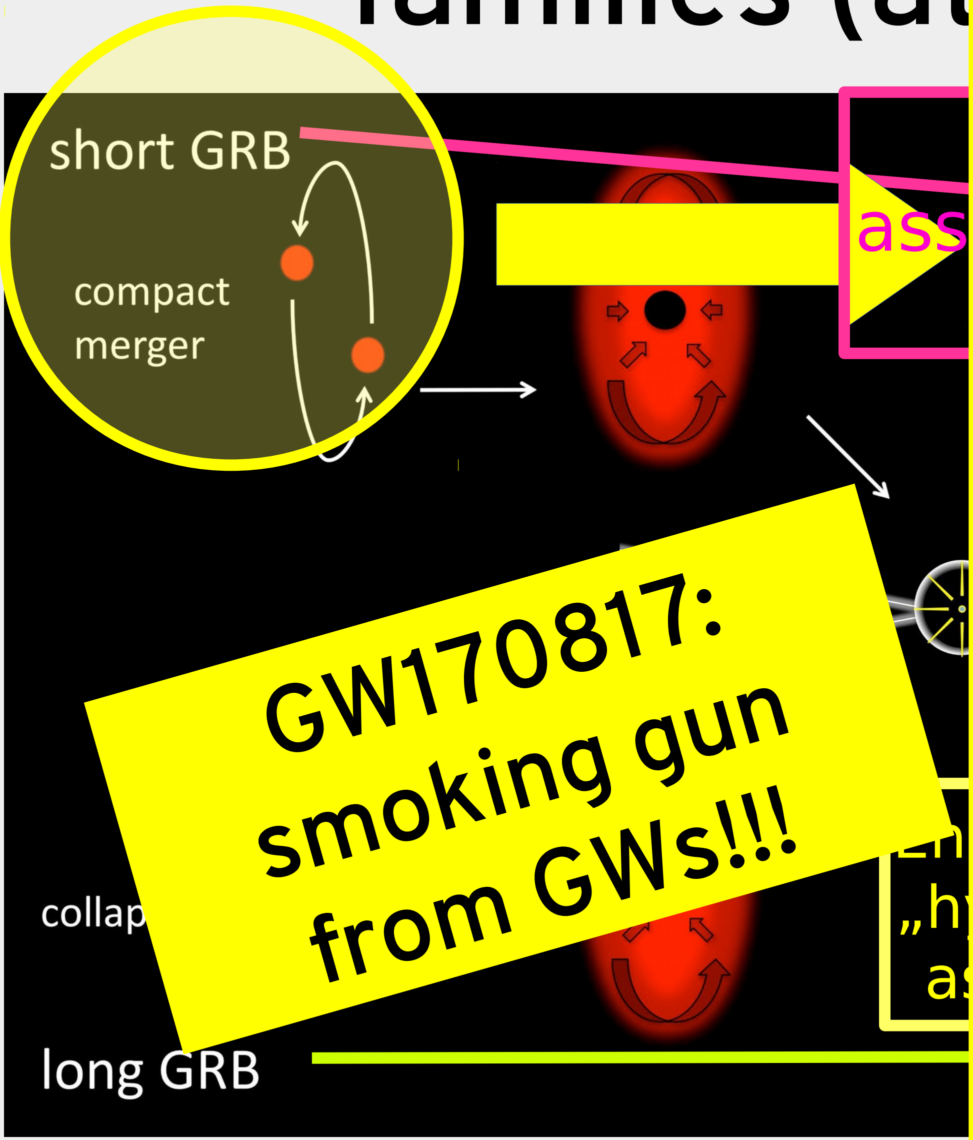


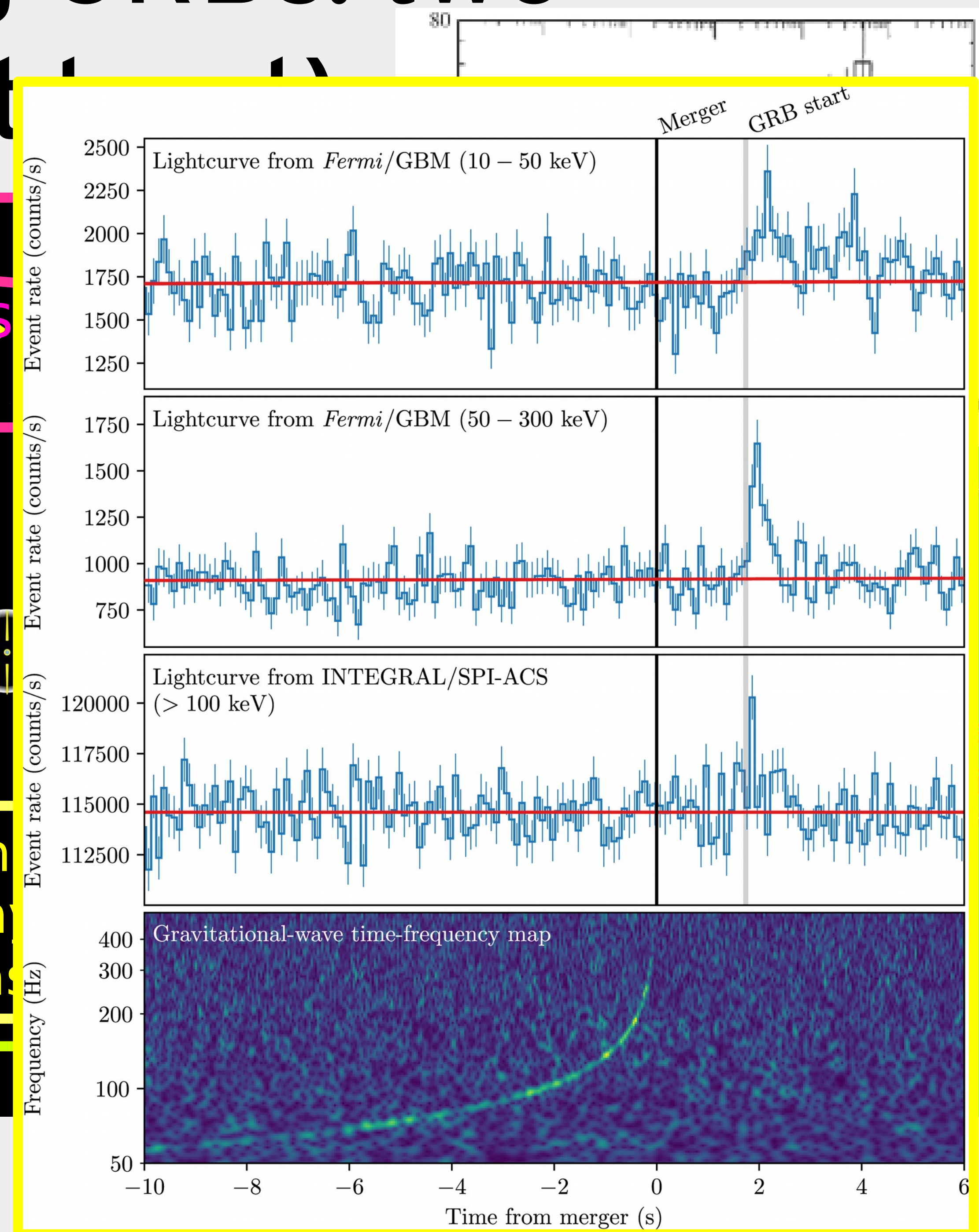
(Berger+13, ApJ)

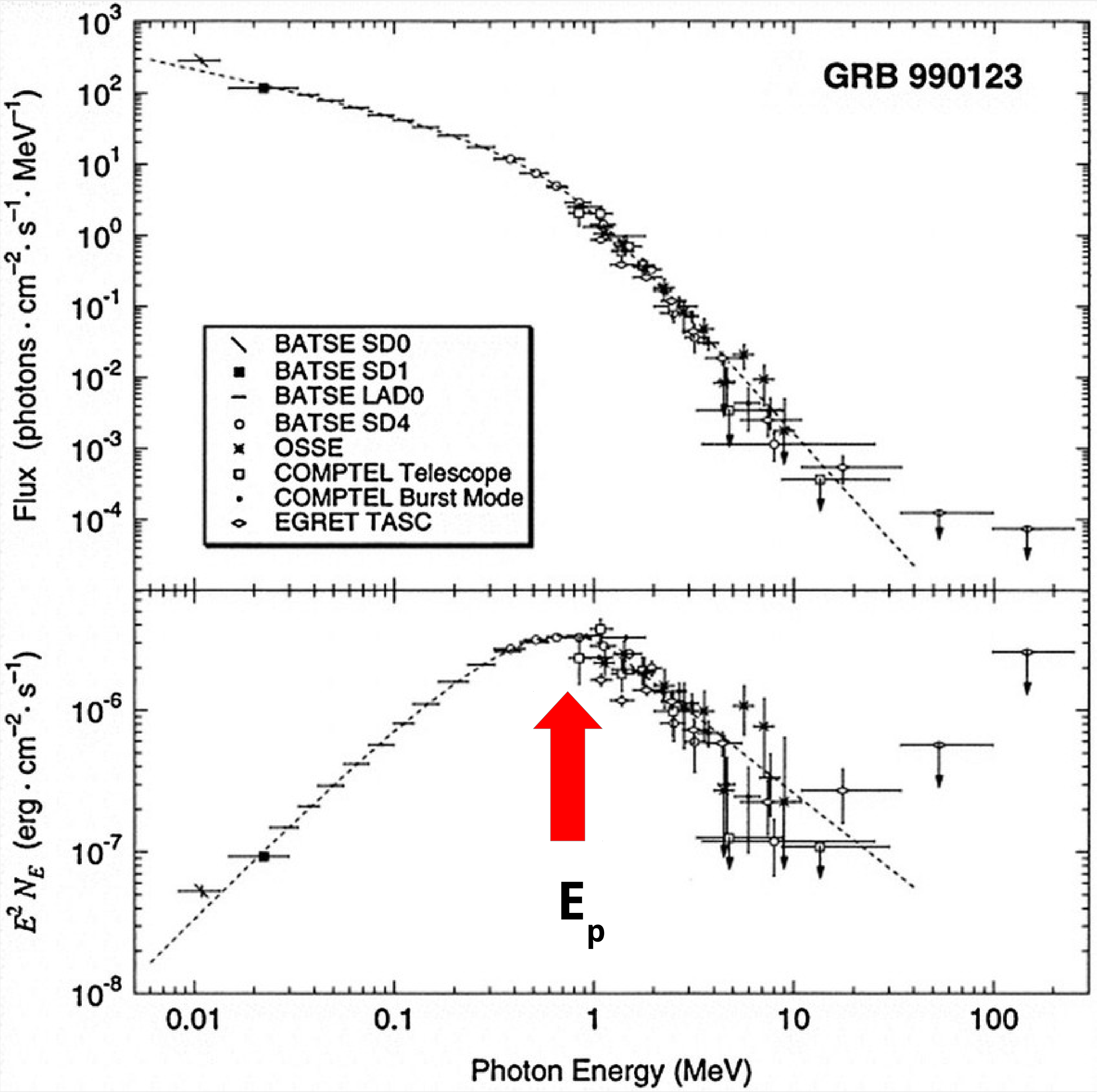
Short and Long GRBs: two families (at least)



Short and Long GRBs: two families (at

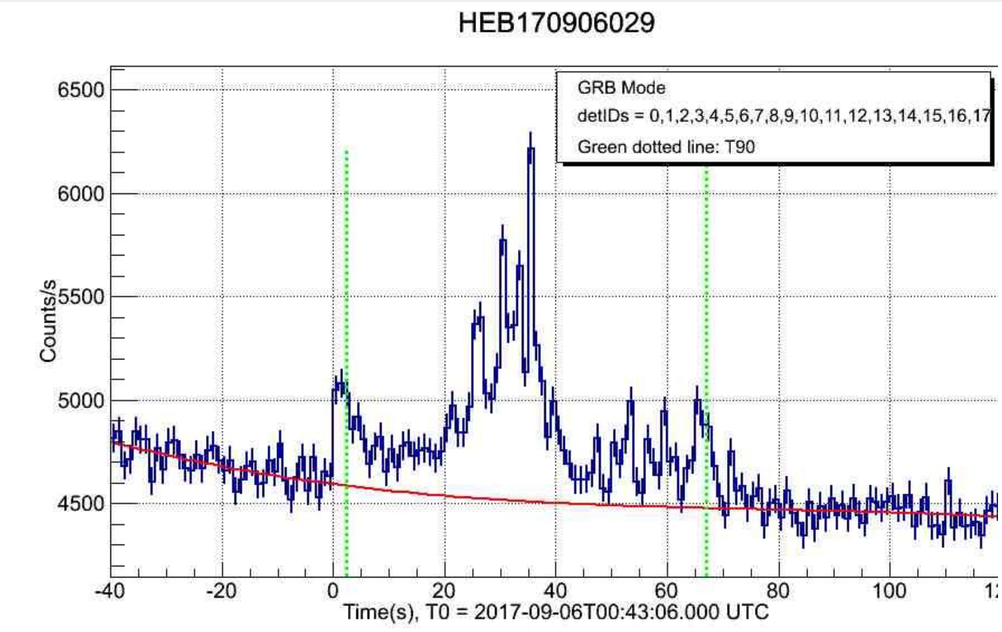




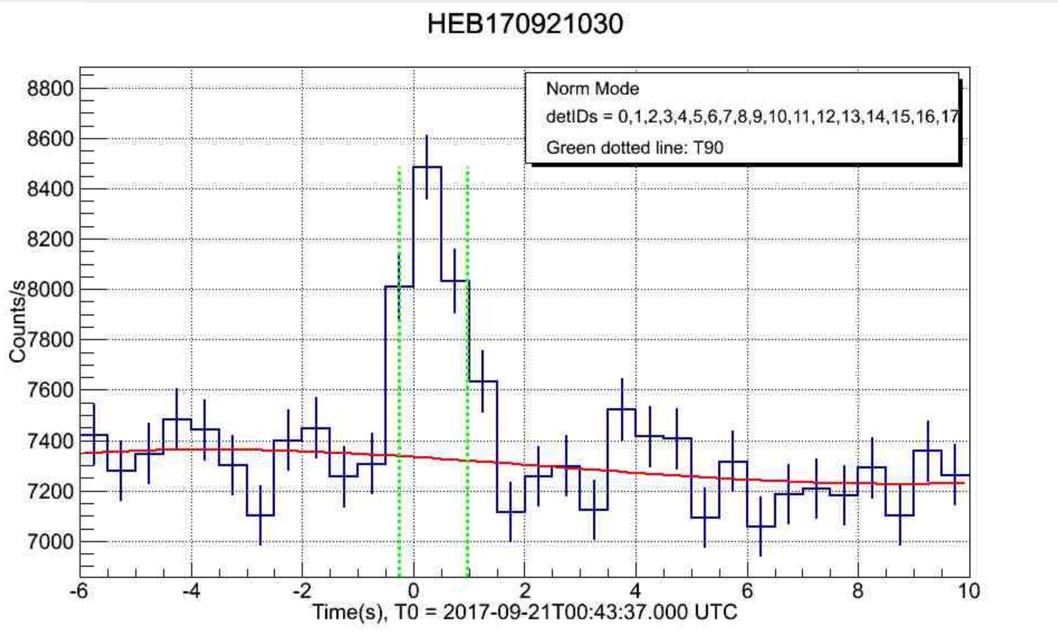


Typical non-thermal spectrum of a GRB: Band function

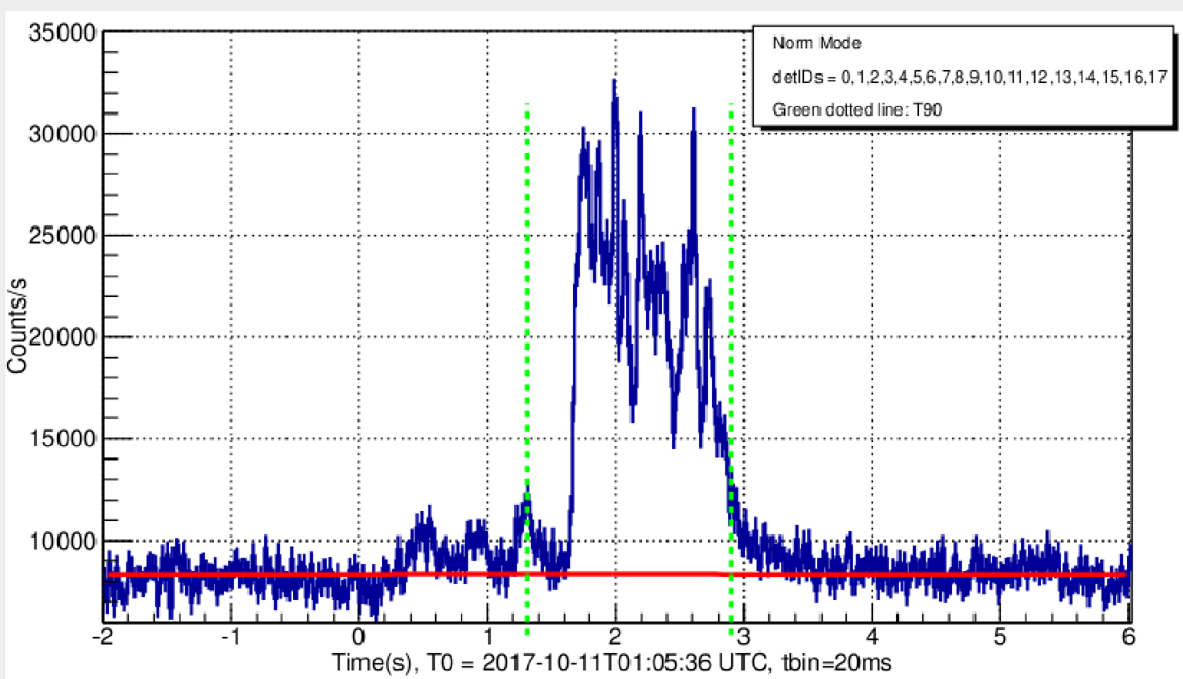
Real data: background looks way better



GRB 170906: GCN 21921

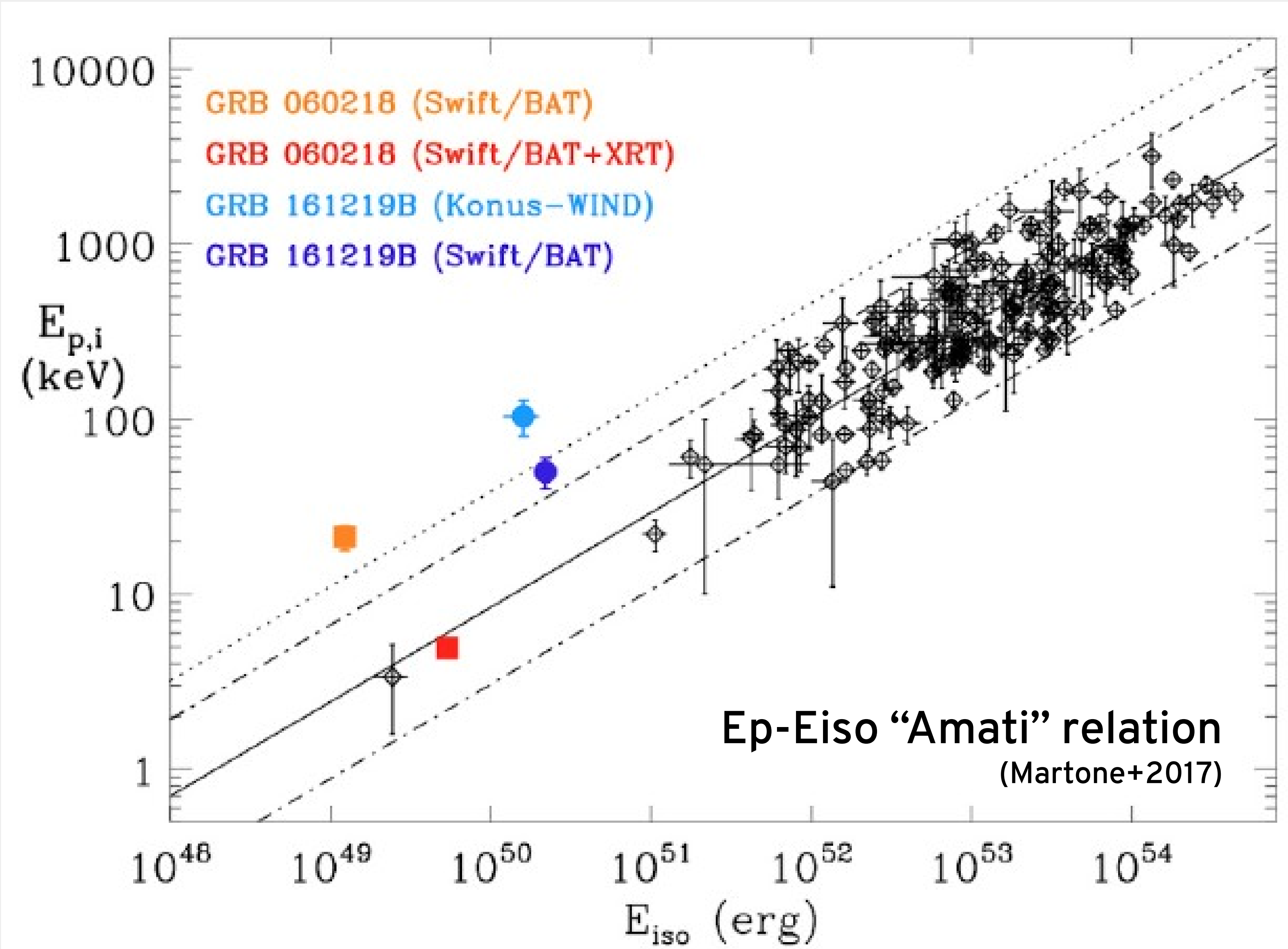


GRB 170921: GCN 21919

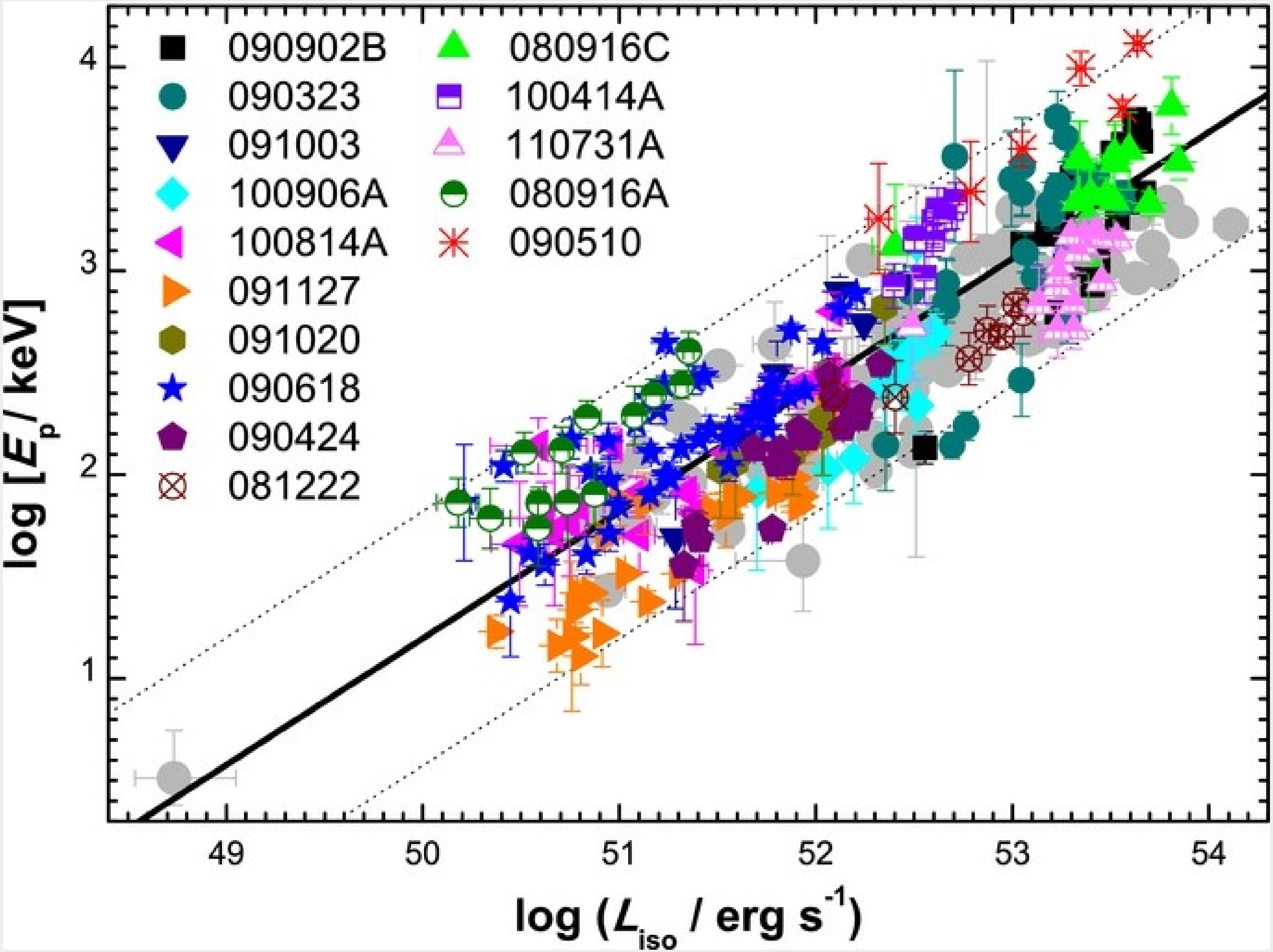


GRB 171011B: GCN 22026

E_p: key to GRB physics and as a cosmic ruler

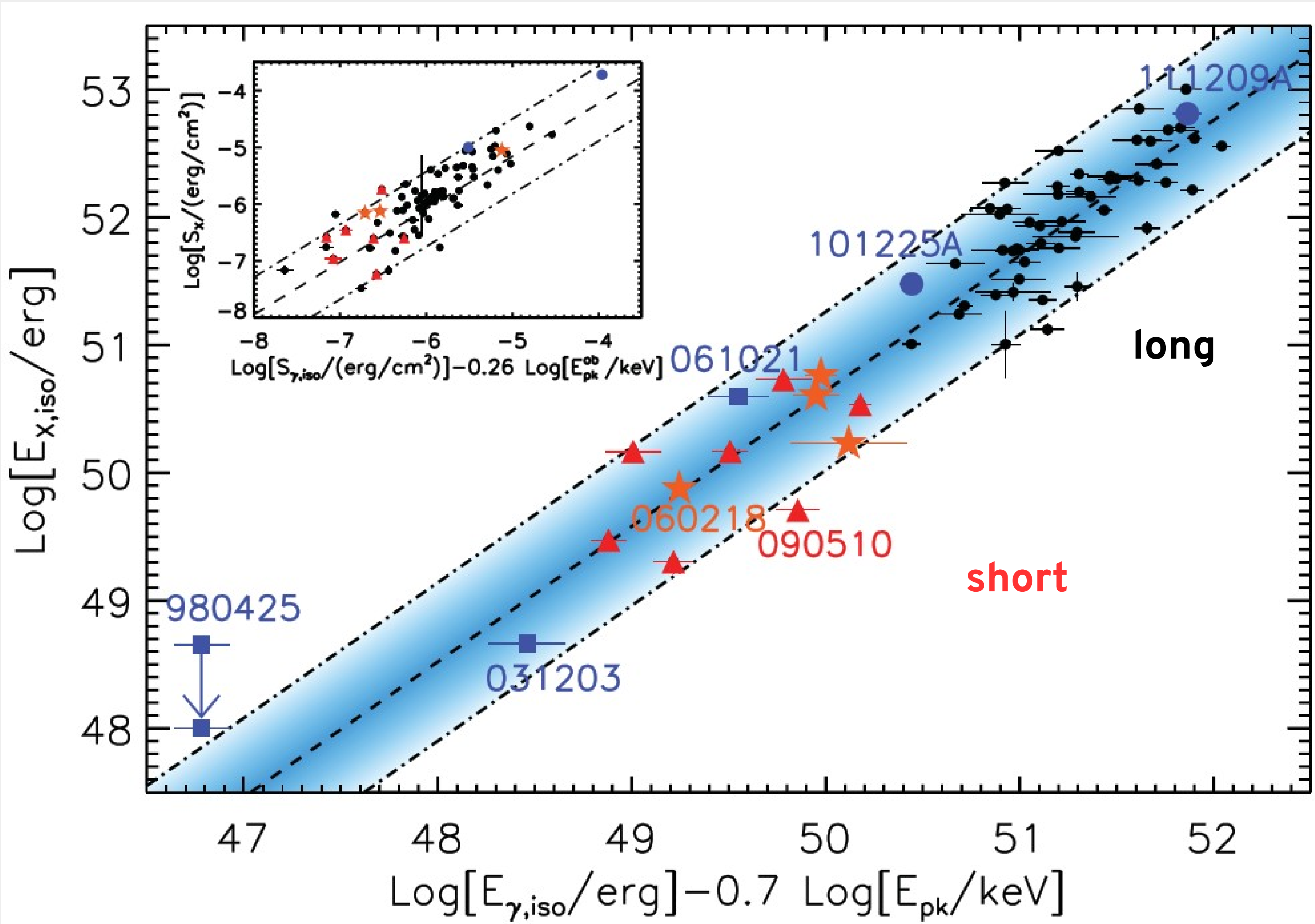


Time-resolved L_p - E_p



(Lu+2012)

Three-parameter relation E_p - $E_{X,iso}$ - $E_{\gamma,iso}$



(Bernardini+, 2012; Margutti+2013; Zaninoni+2016)

Comeback of sub/photospheric models

- Recently, so-called (sub)photospheric models gained more credit compared with the traditional internal shock model (in which the prompt is produced at $R >> R_{phot}$ through shocks that convert kinetic into radiated energy)

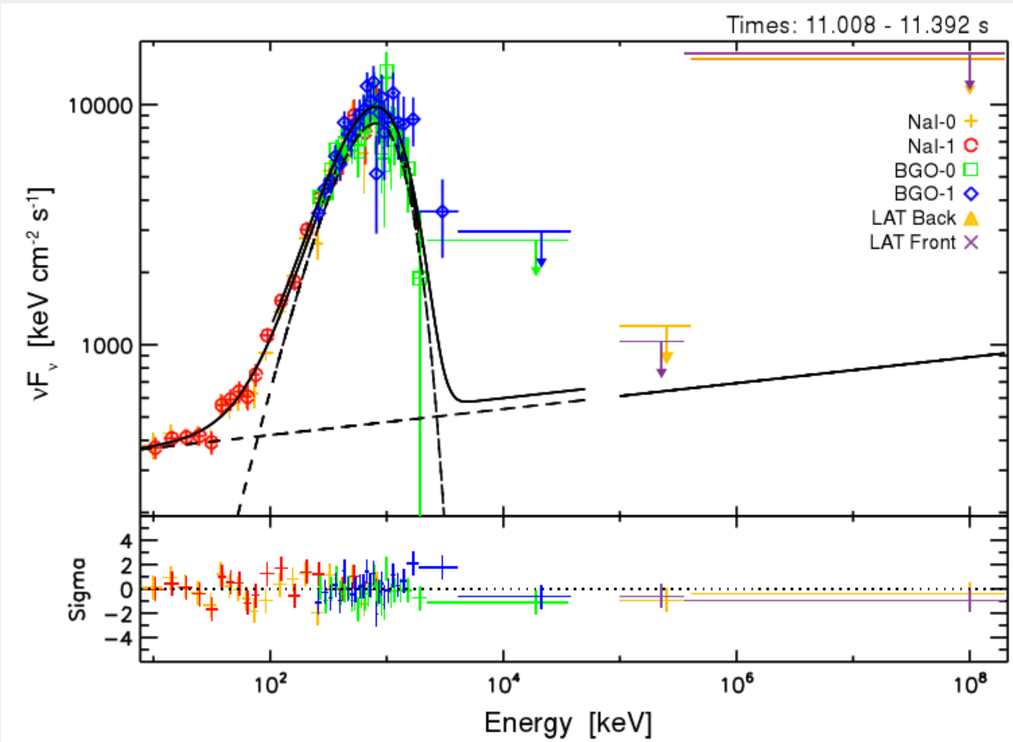
- Establishing the presence of (sub)dominant photospheric components (BB or BB-like) in time-integrated (resolved) requires a precise measurement of all components

- A large effective area coupled with broadband spectroscopy capabilities becomes a must → HXMT

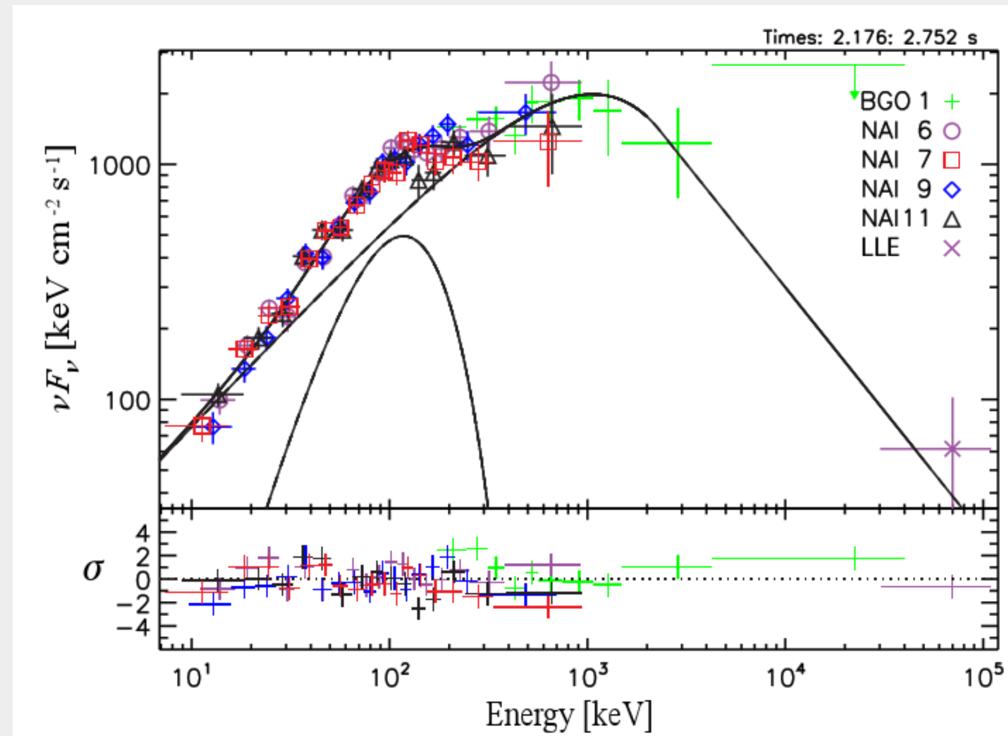
Thermal component identification

GRB 090902B: BB+PL

GRB 110721A: Band+BB



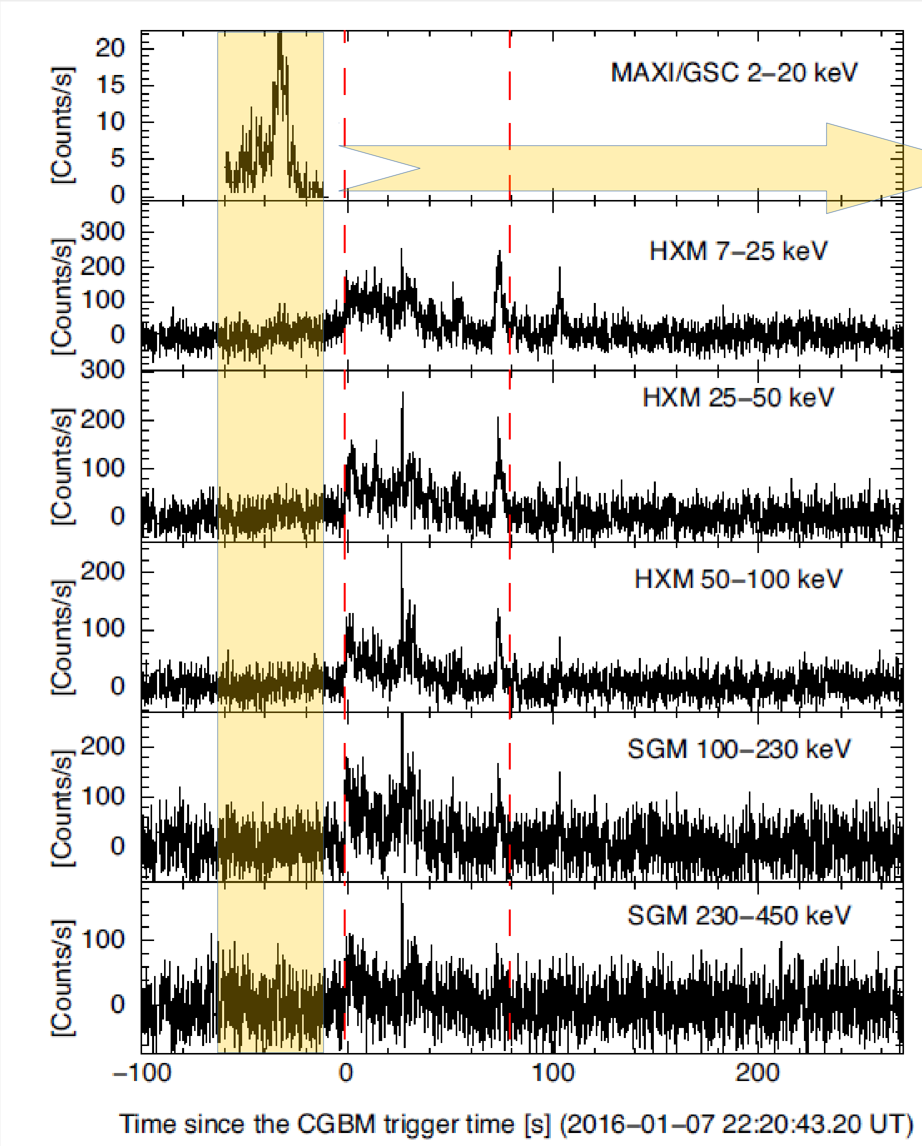
(Ryde+ 2010)



(Axelsson+ 2015)

A sensitive, broad-band coverage up to few MeV is crucial -especially for intermediate fluence GRBs- to assess the presence of dominant/subdominant thermal components in addition to typical non-thermal (PL, Band) spectra

Thermal emission in GRB160107A precursor



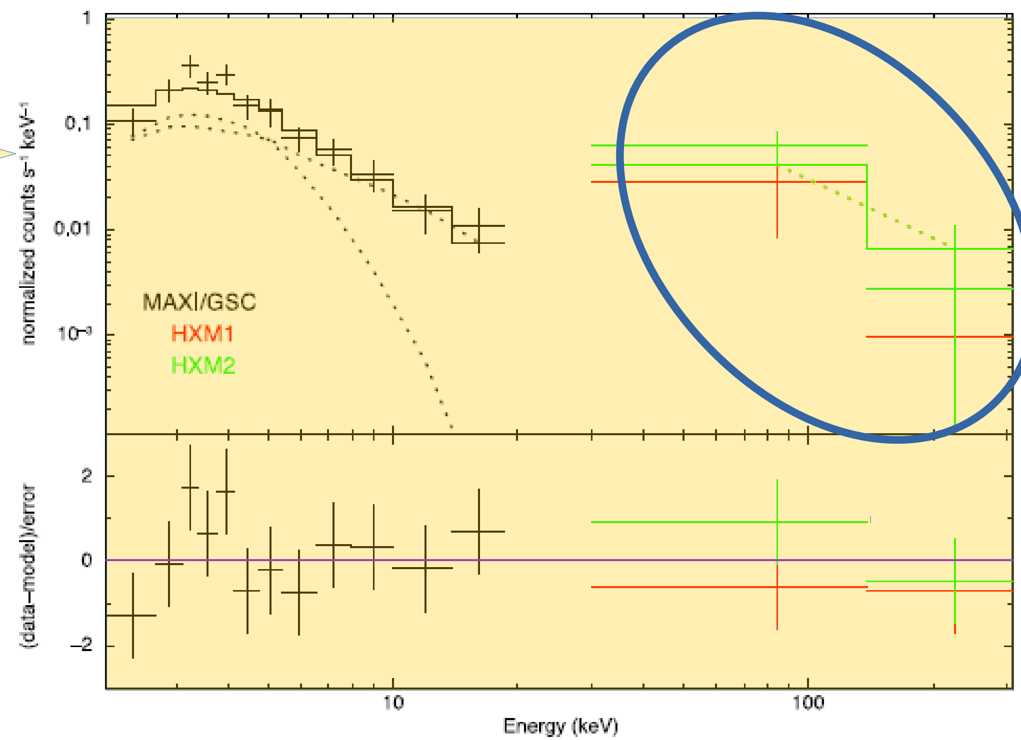


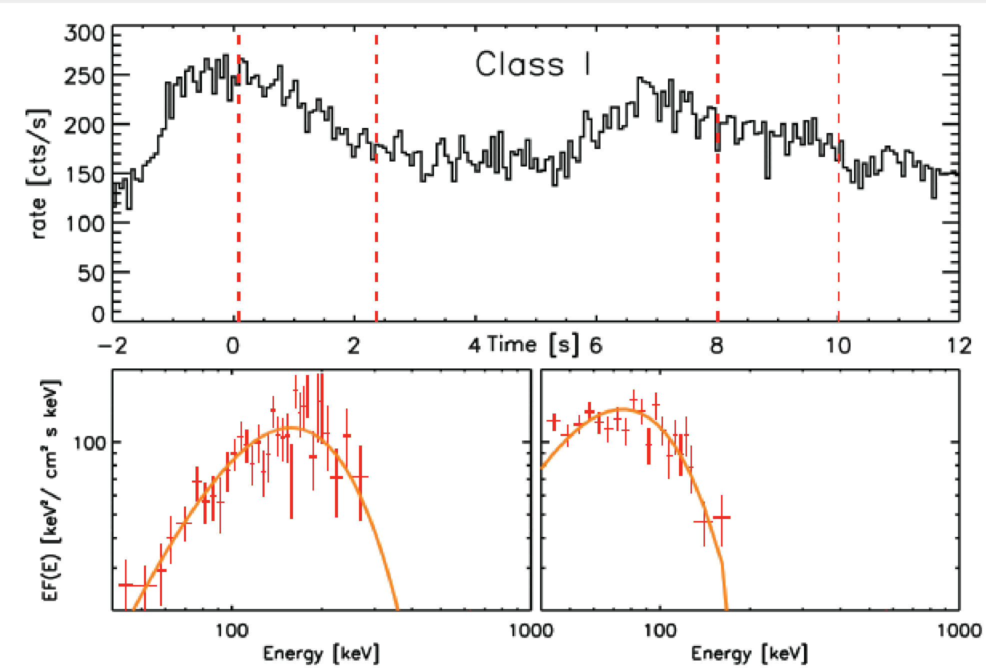
Fig. 5. Time-averaged spectrum of the prior emission with a best-fit PL + BB model. The black, red, and green points are the MAXI/GSC, the HXM1, and the HXM2 data, respectively. The best-fit model is PL + BB.

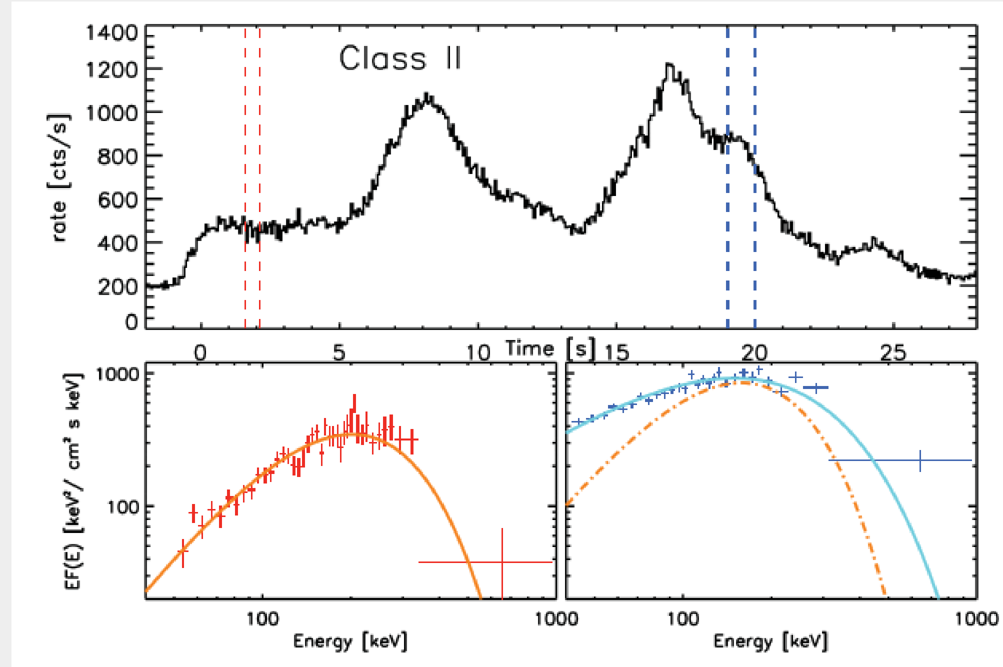
MAXI + CALET

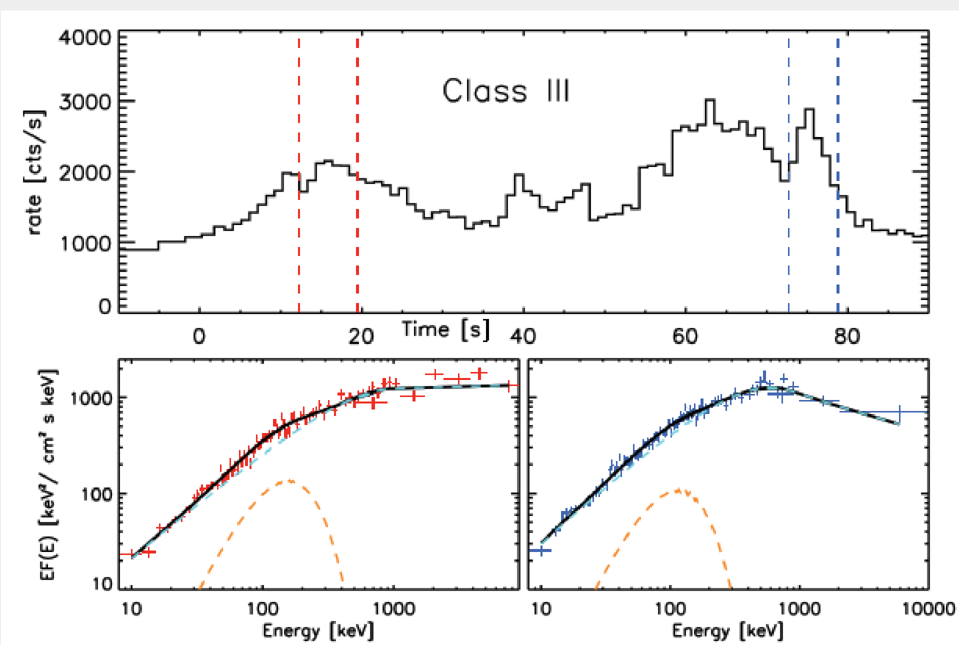
(Kawakubo+ 2018)

A large effective area at several 100 keV is key to assess the plausibility of a multi-component modeling

Photospheric emission: different evolutions







A possible thermal component may show up in different ways:

(1) throughout the entire GRB as a dominant component (class I)

(2) just at the beginning and then fade away (class II)

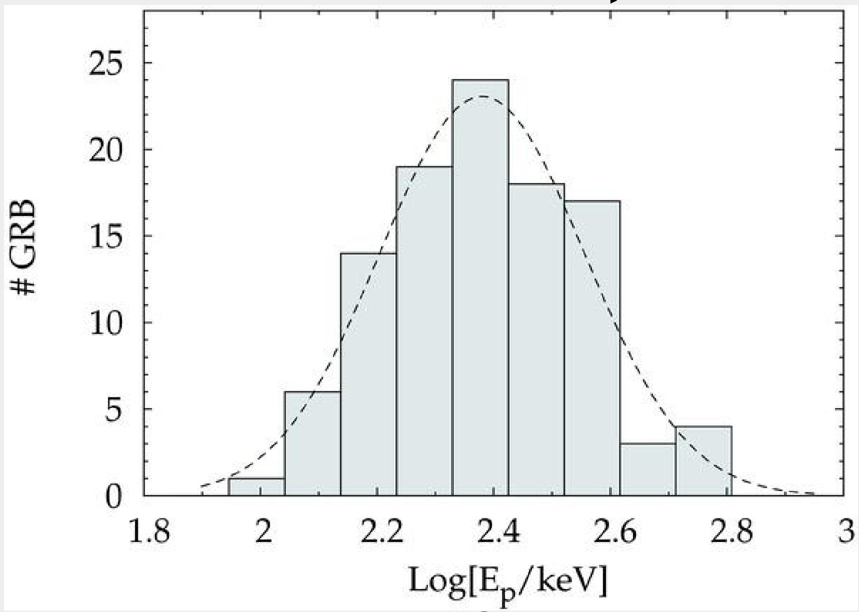
(3) Throughout the entire GRB as a subdominant component with a few % fluence (class III)

(Ghirlanda+ 2013)

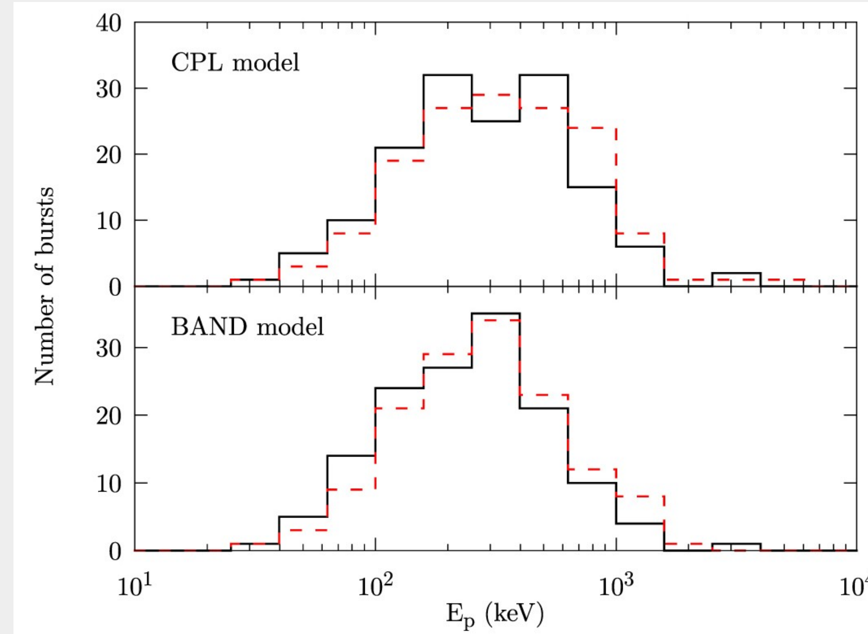
Observed ensemble properties of GRB prompt emission

Observed E_p distributions

Long GRB

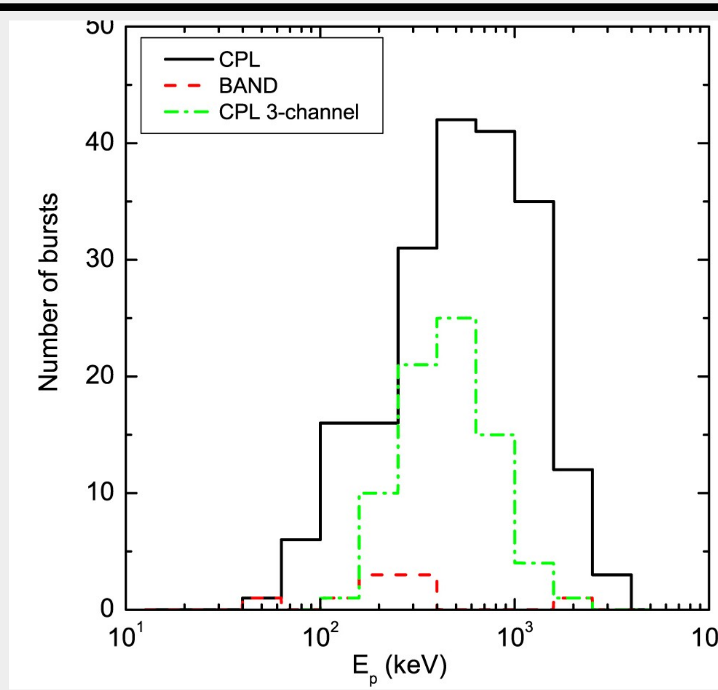


BeppoSAX (CG+11)



Konus (Tsvetkova+17)

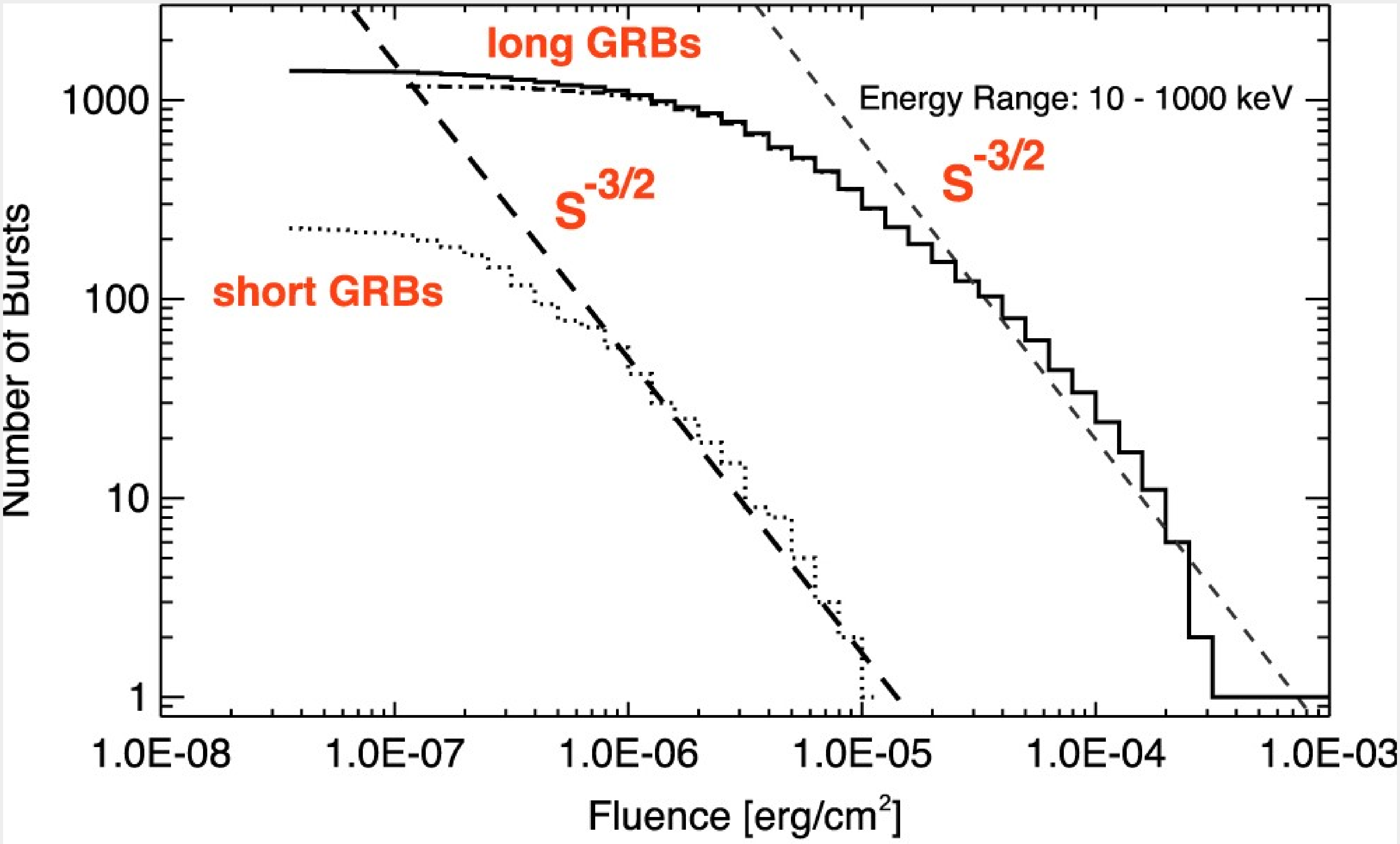
Short GRB



Konus (Svinkin+16)

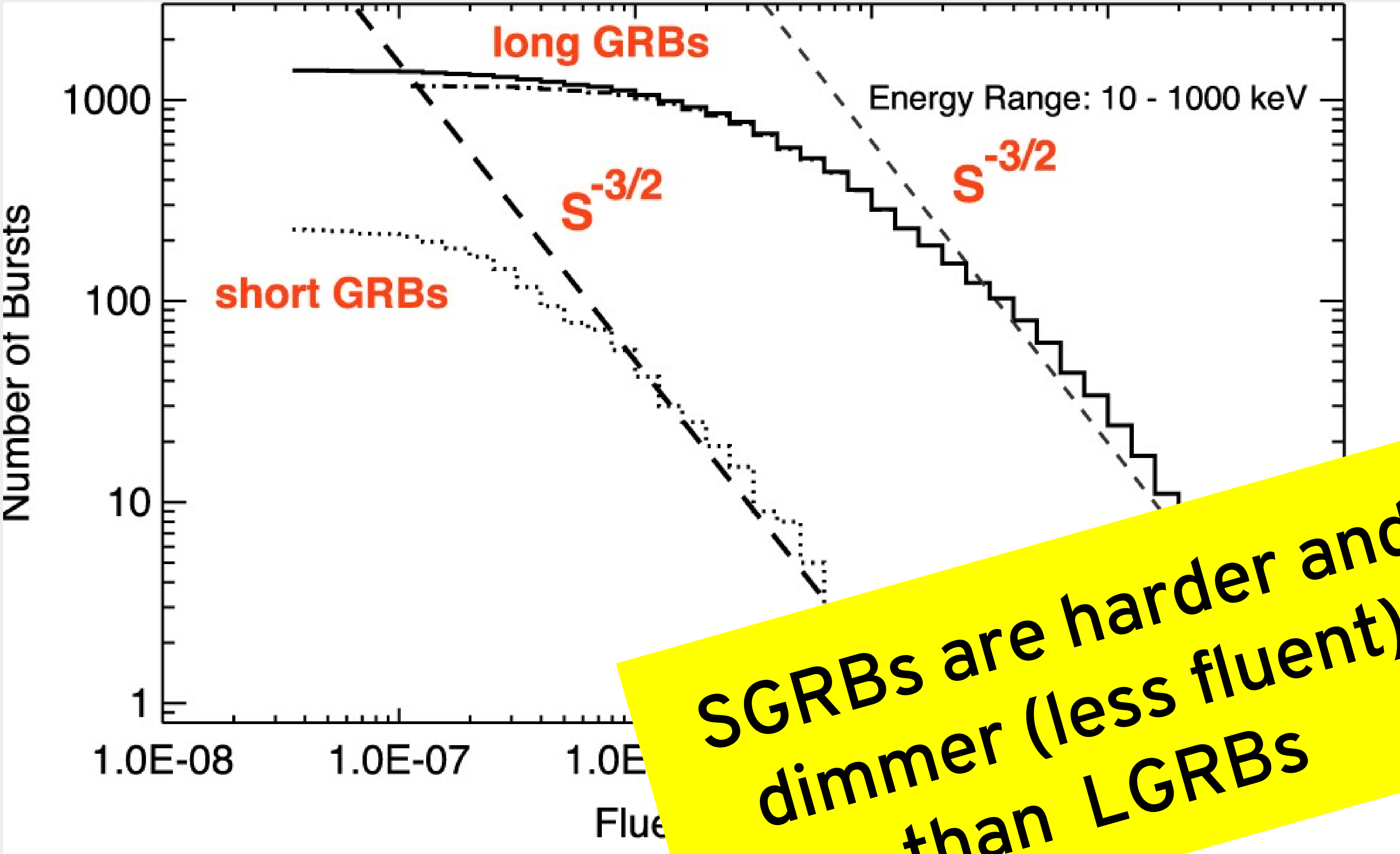
Higher Ep for SGRBs (on average)

Observed fluence (10 keV – 1 MeV) distributions



Fermi/GBM catalogue (Bhat+16)

Observed fluence (10 keV – 1 MeV) distributions



Fermi/GBM catalogue (Bh

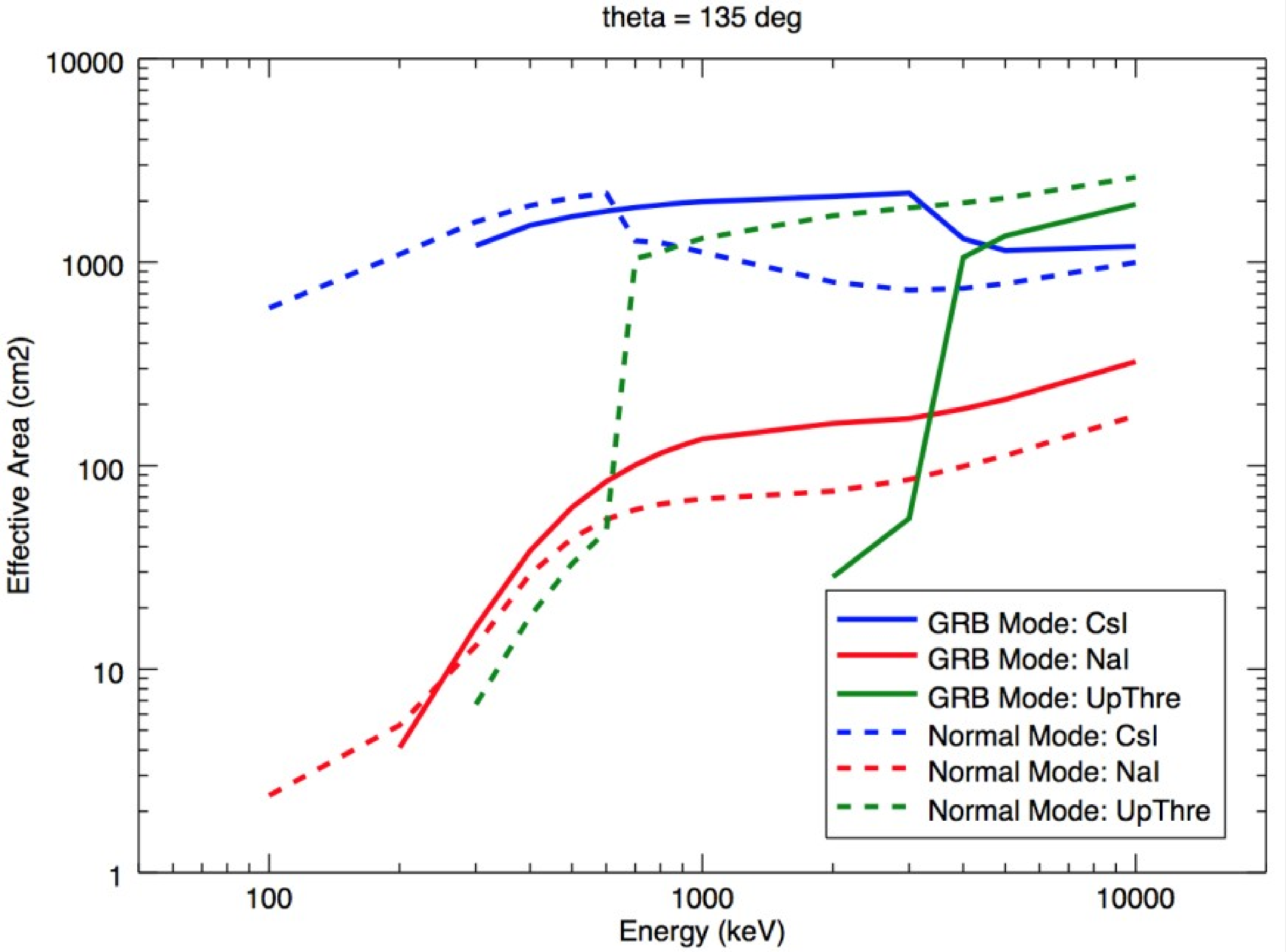
SGRBs are harder and dimmer (less fluent) than LGRBs

Simulations

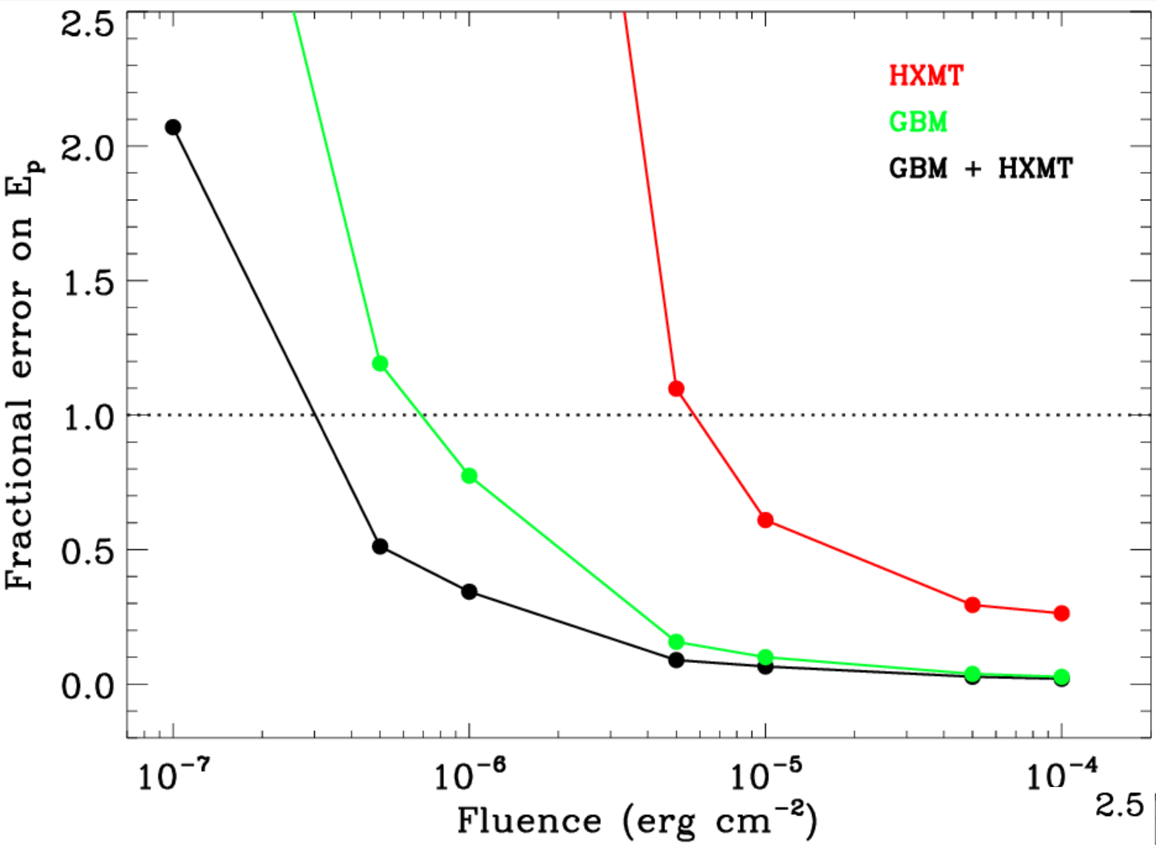
Direction: 135 deg (rear)
HE mode: GRB

Response Function:

- total 18 CsI units
- 200 keV – 3 MeV
- 256 energy chan

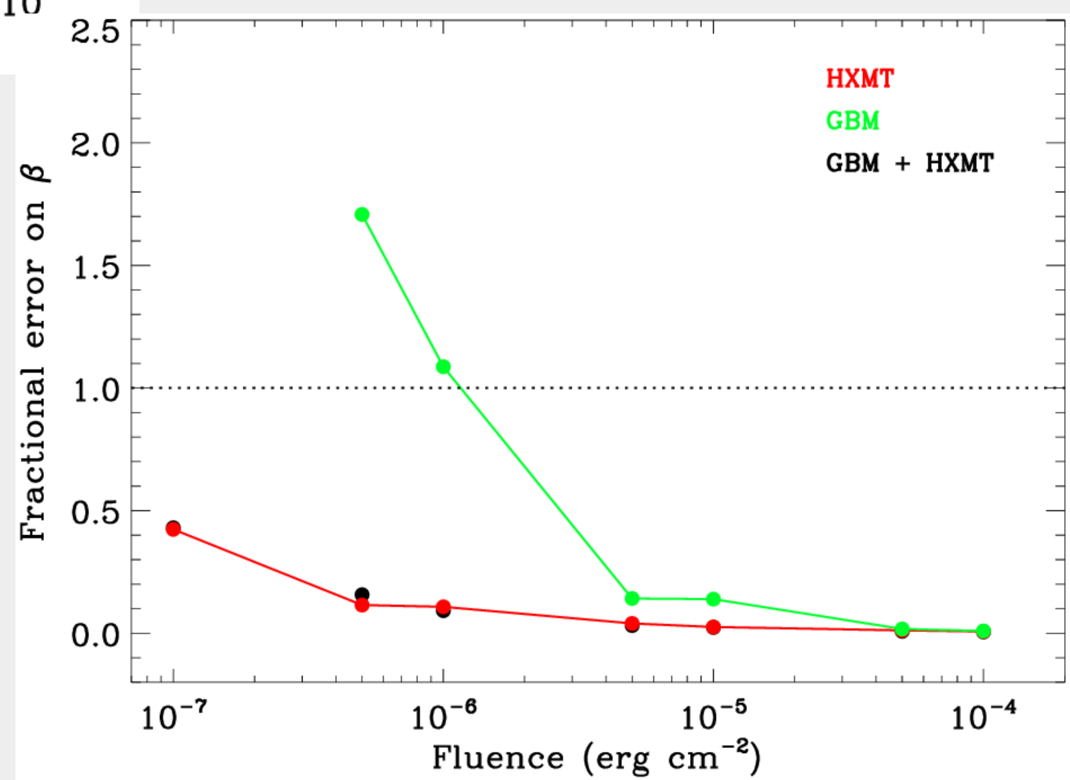


(Kindly provided to us by Shaolin Xiong on Feb 2017)

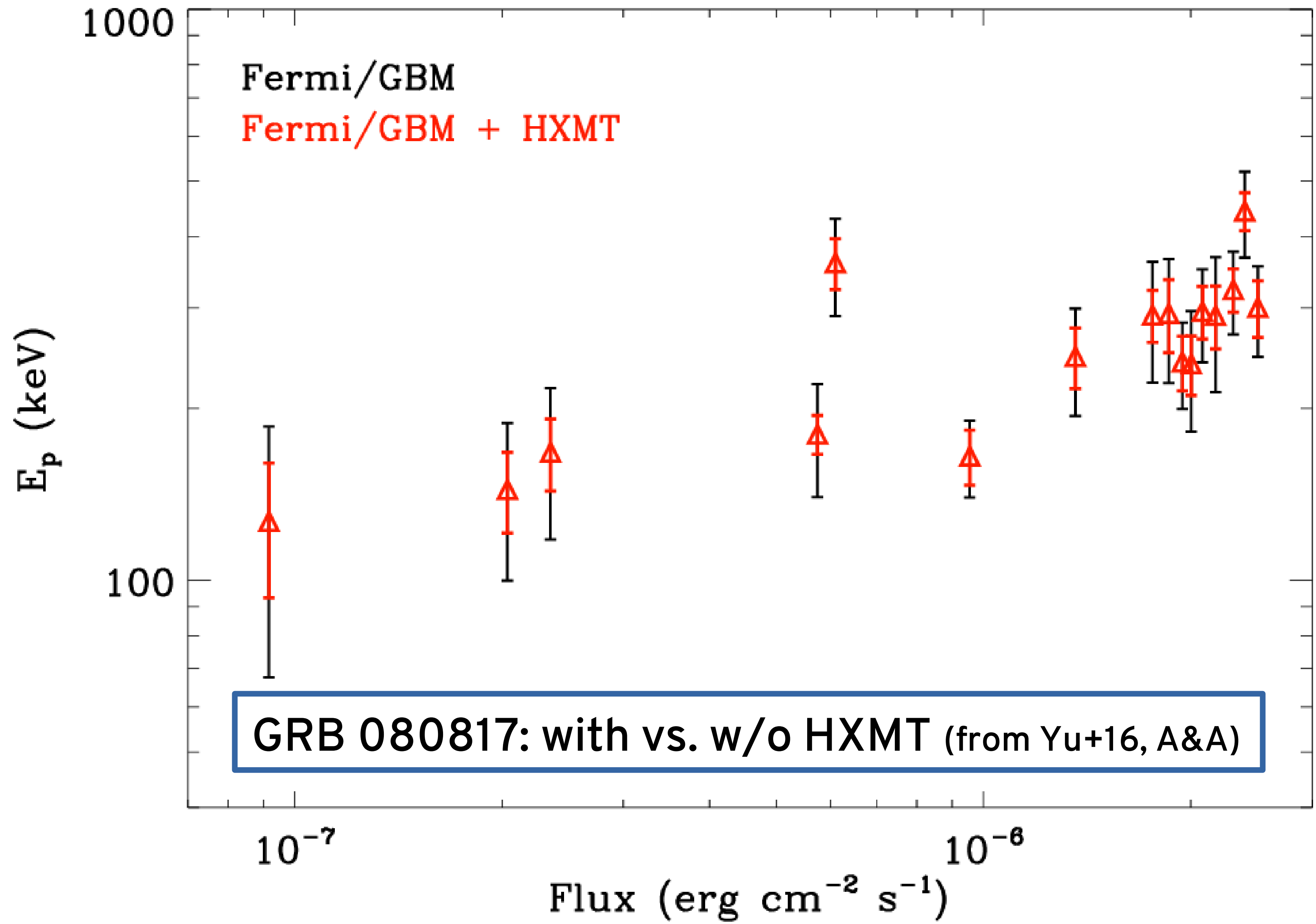


Joining GBM+HXMT greatly improves accuracy on Ep for $\Phi < 10^{-5}$ erg cm^{-2}

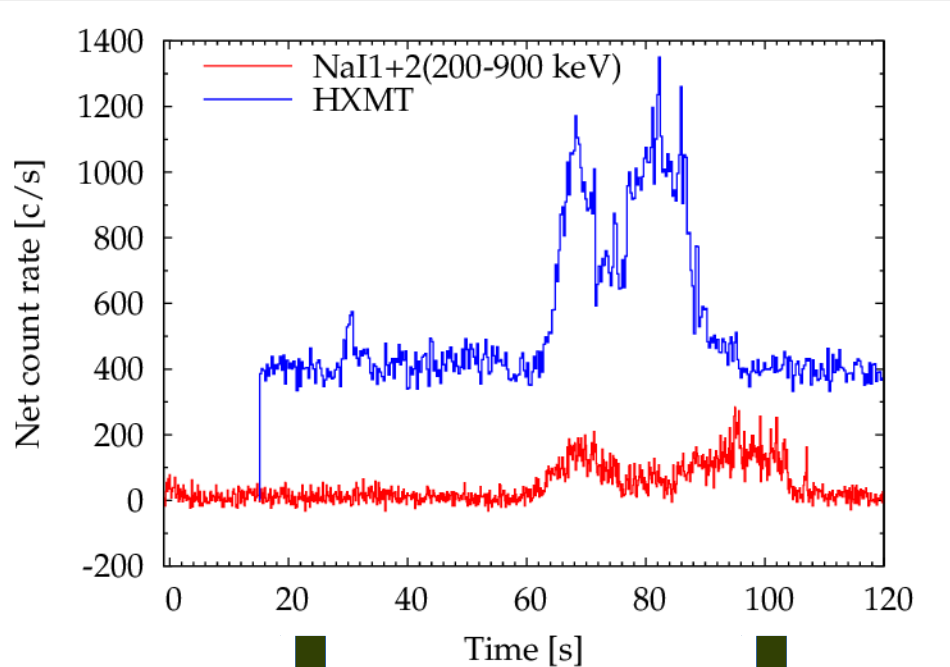
The same holds for the high-energy photon index β



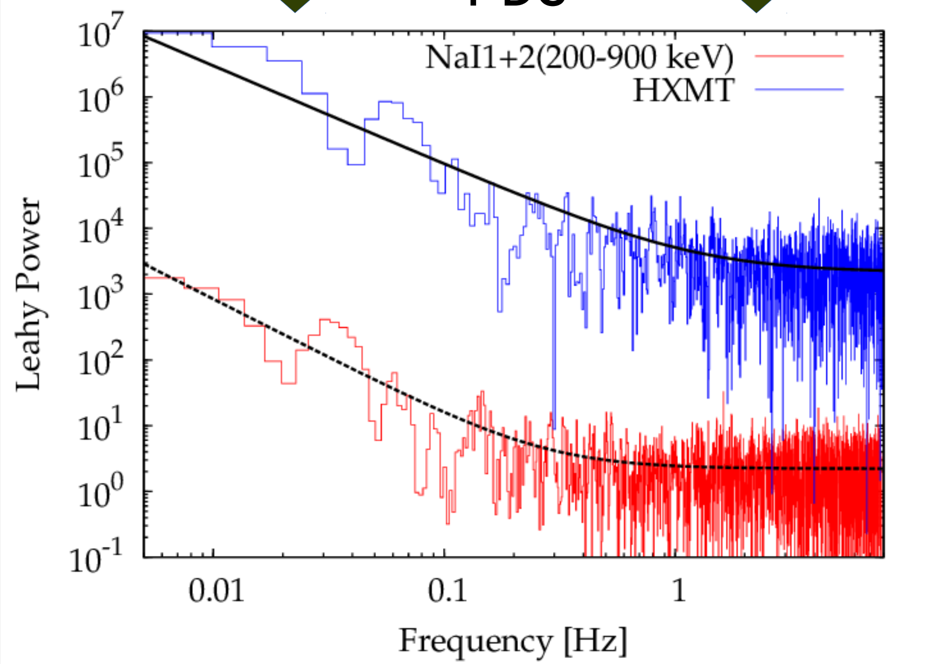
Time-resolved E_p: the HXMT added value



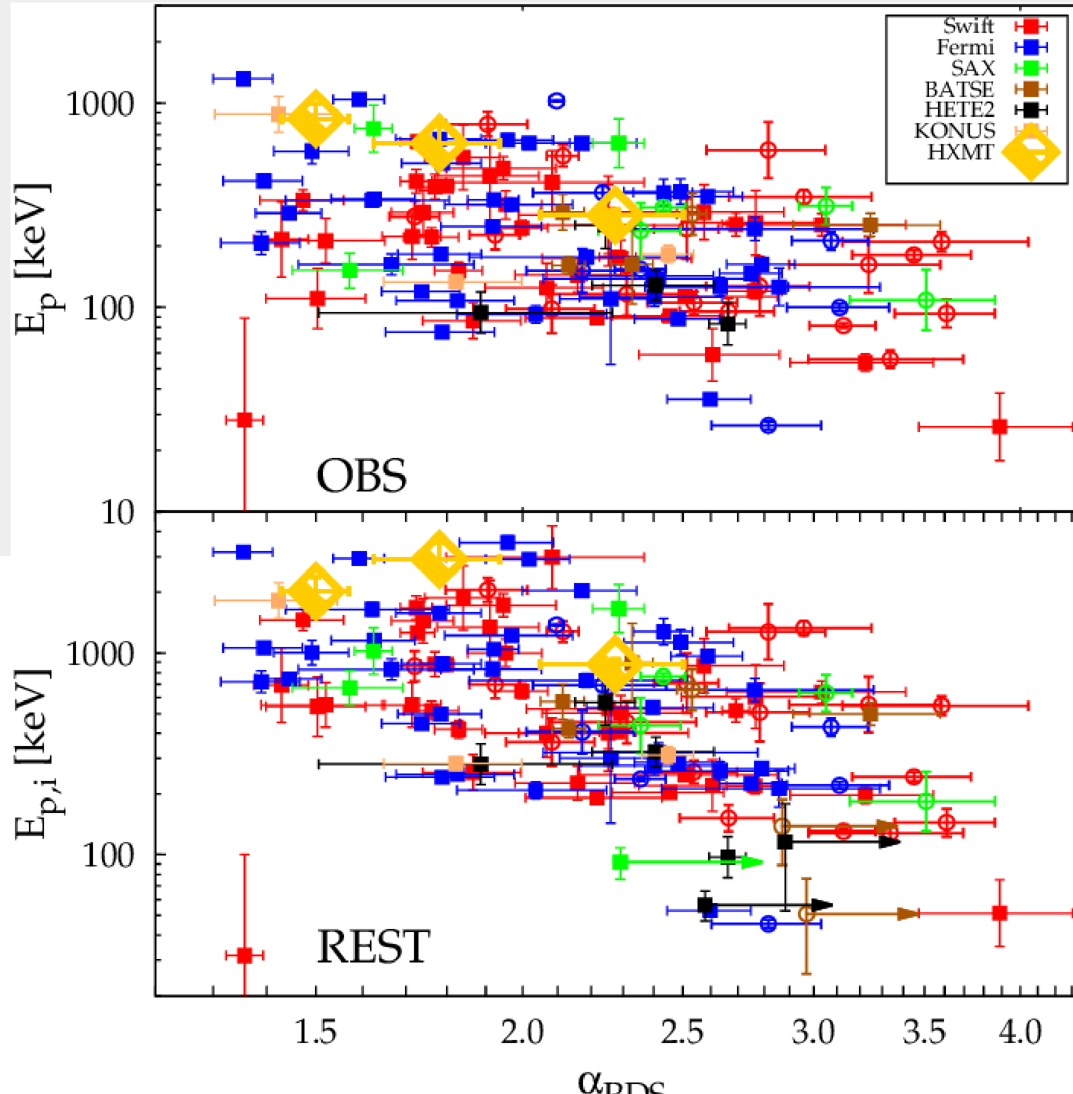
Simulated LC (HXMT vs Fermi-GBM)



PDS



Ep,i – Slope(PDS) relation



(adapted from Dichiara+16, A&A)

Expected Detection Rate: ~200/yr

Significance (sigma)	GRB mode GRBs/year		Normal mode GRBs/year	
	Front	Back	Front	Back
5	70	130	85	145
10	40	110	50	135
20	20	80	25	115

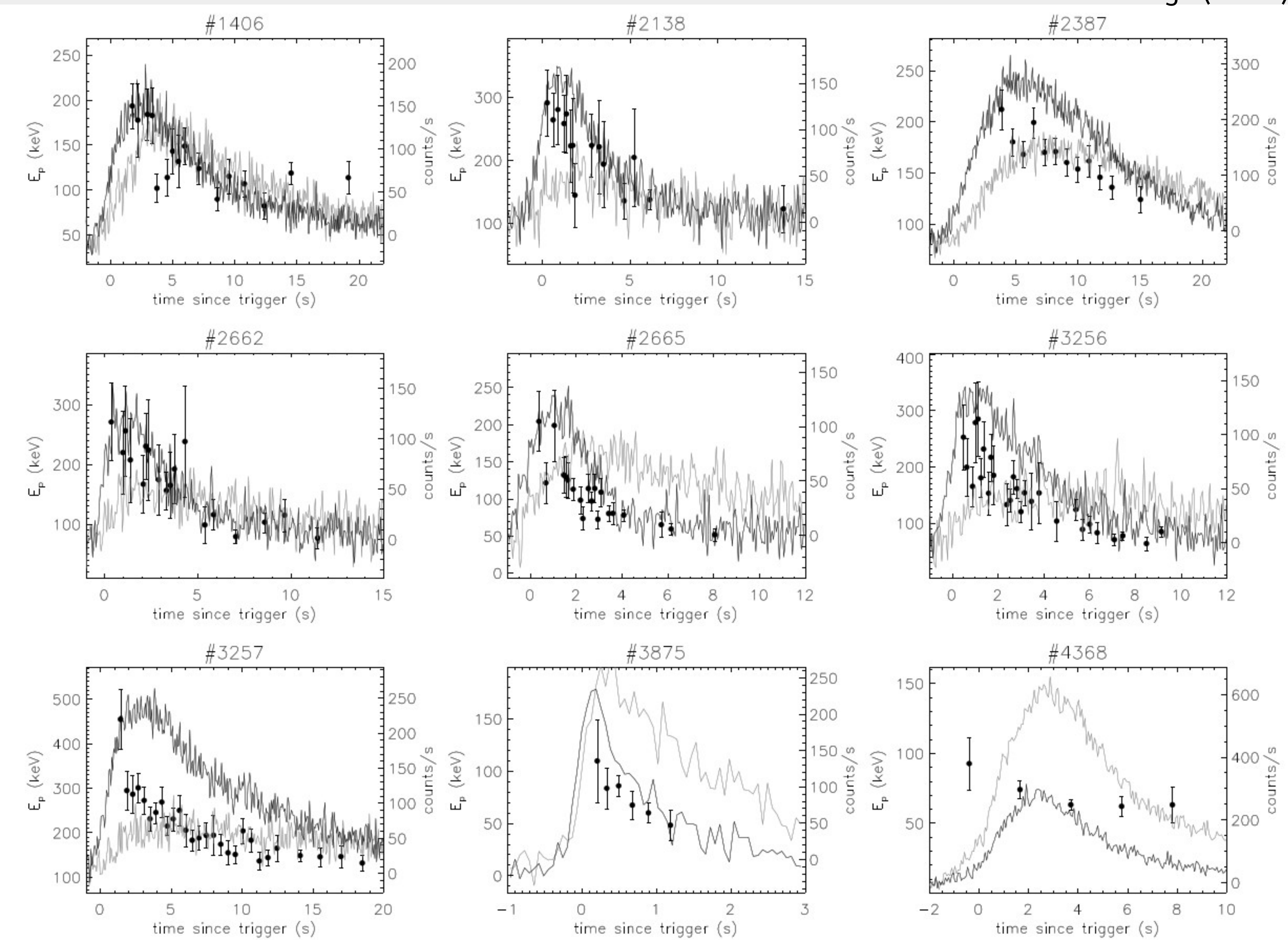
~30% short

~50% in common with Swift and/or Fermi and bright enough to enable spectral analysis

What is the (spectral) lag?

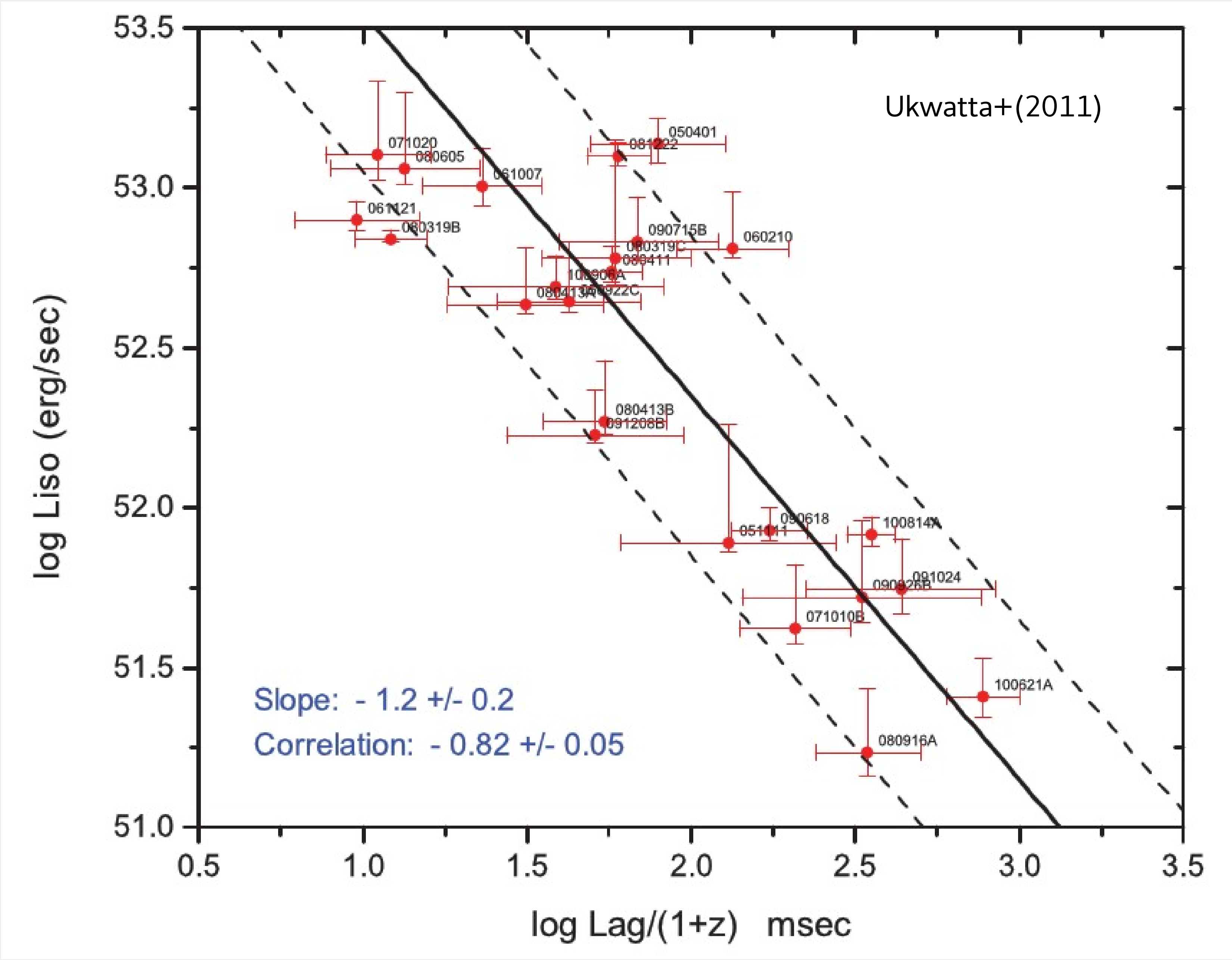
"Sort of delay between time profiles of the same GRB as seen in different energy channels"

Peng+(2011)



Hard-to-soft spectral evolution

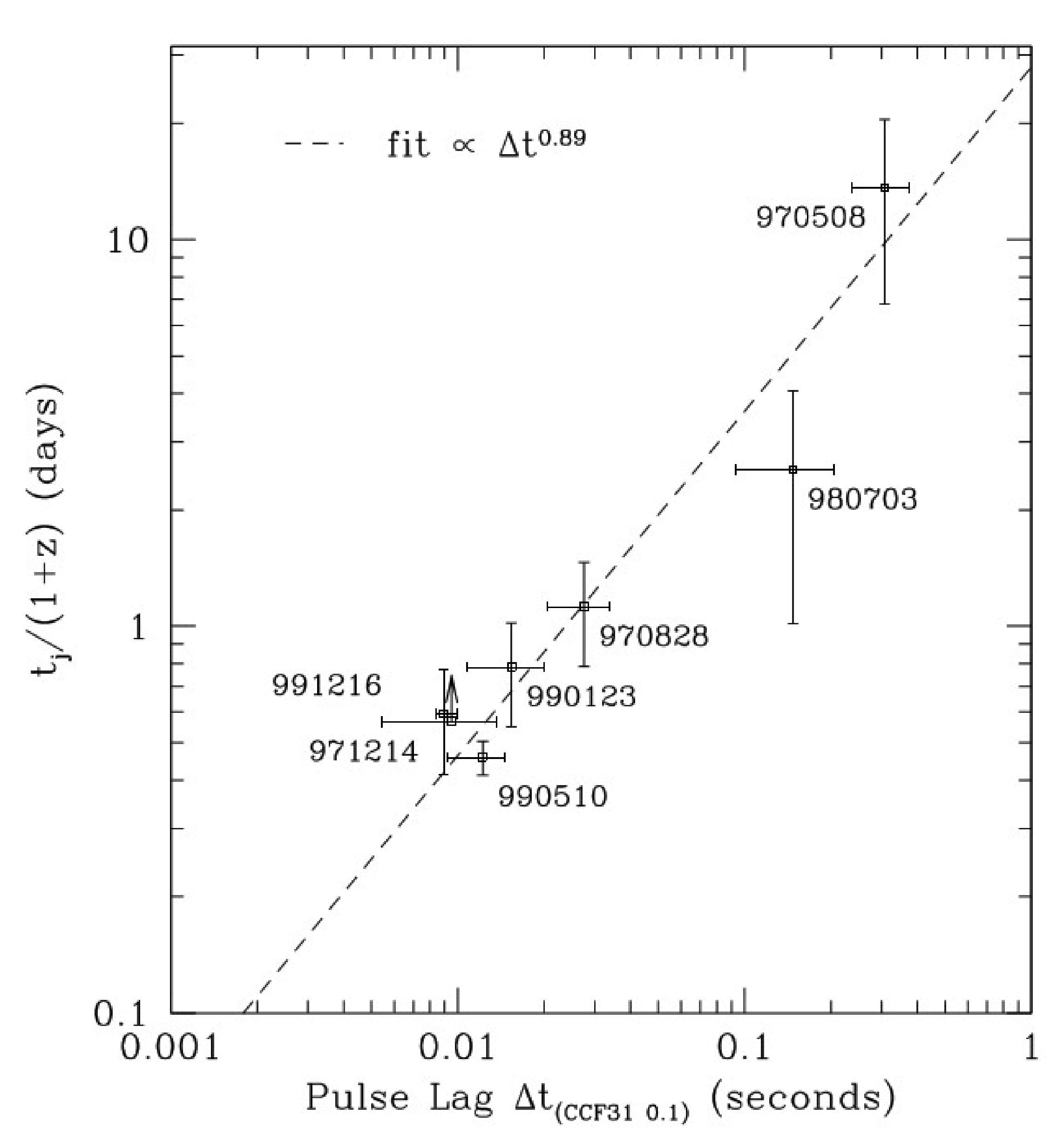
Lag-Luminosity holds for Swift long GRBs as well



Swift GRBs (BAT data): **100-150 keV** vs. **200-250 keV** (**rest frame!**)

Lag is likely a key parameter connecting prompt and afterglow

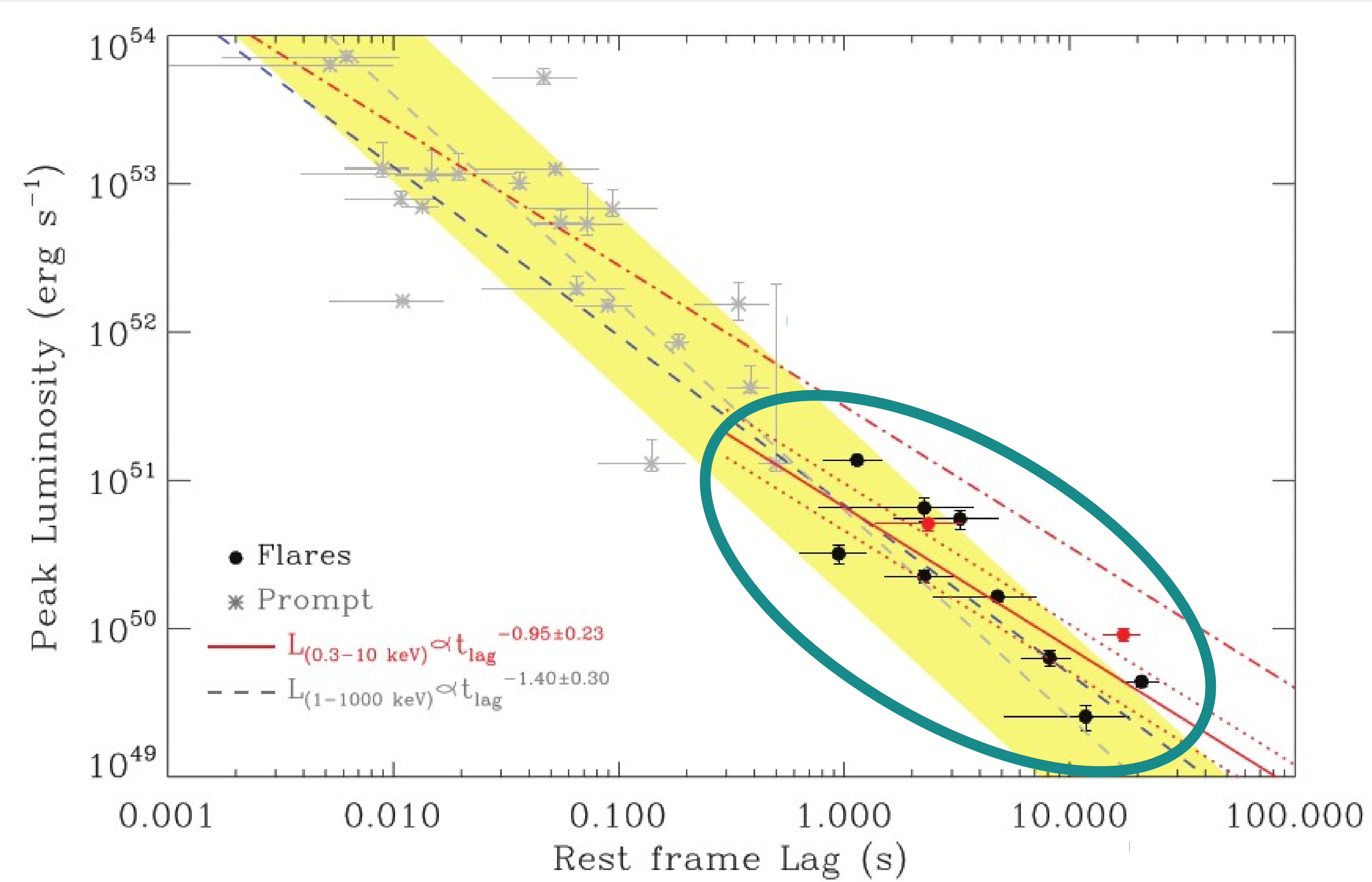
Salmonson & Galama (2002)



Lag and jet break time appear to be correlated

t_j = jet break time in the optical afterglow light curve

Lag-Luminosity extended to X-ray flares in the X-ray afterglow!



Margutti, Guidorzi +(2010)

Why do we care about lags?

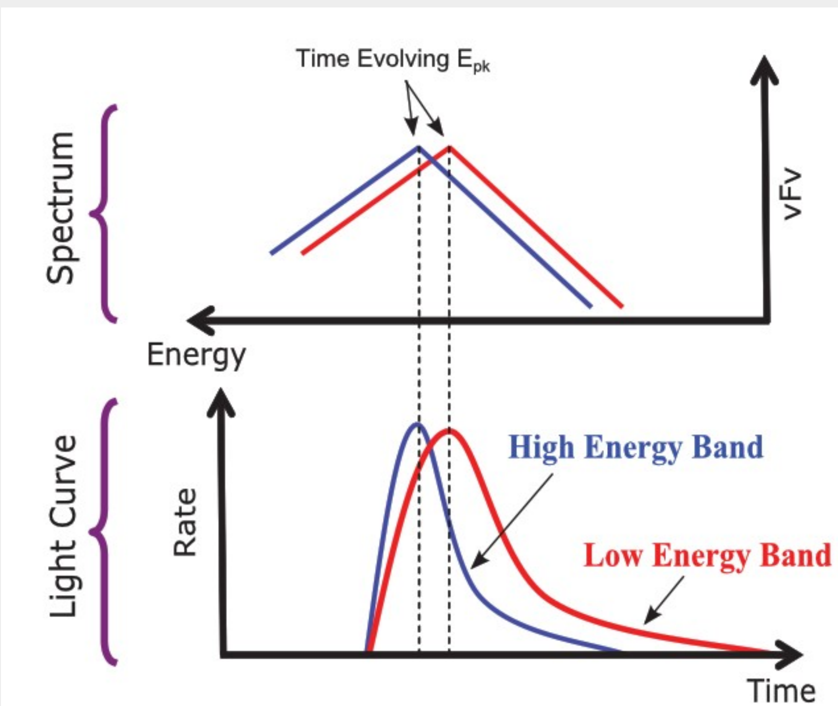
- Lag τ- luminosity L correlation ($L \propto \tau^{-1}$) for long GRBs
- Empirical way of classifying short vs. long GRB (for ambiguous cases)

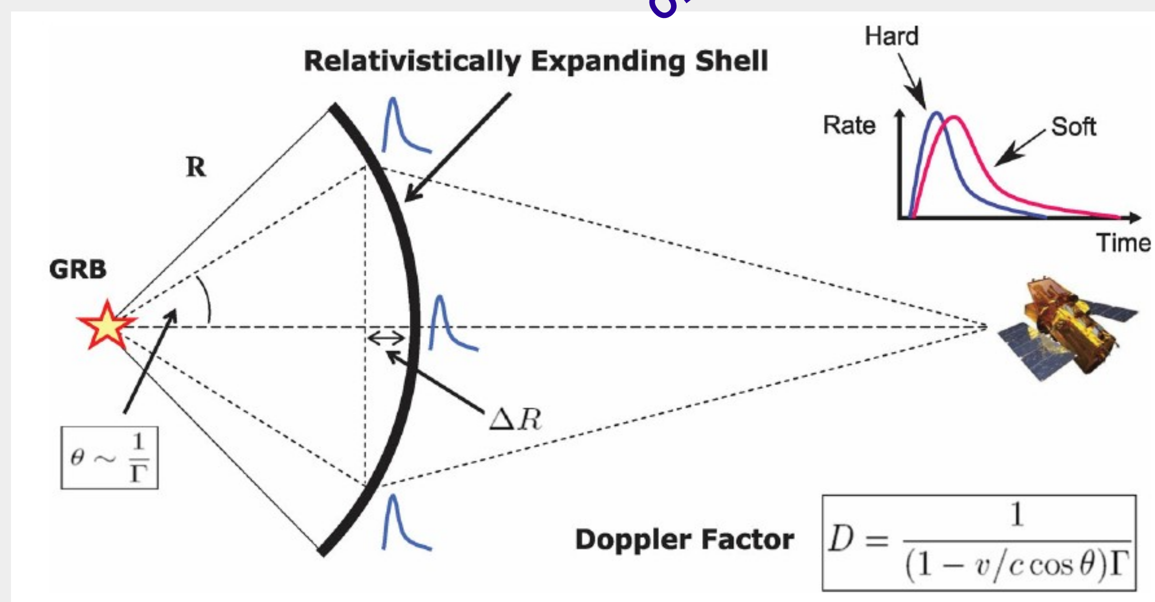
While physical relevant, there's no exhaustive self-consistent explanation

Two main explanations:

- Intrinsic (=within fluid-comoving frame) spectral evolution
- Kinematic/geometric (Doppler factor → Lorentz factor as the key parameter)

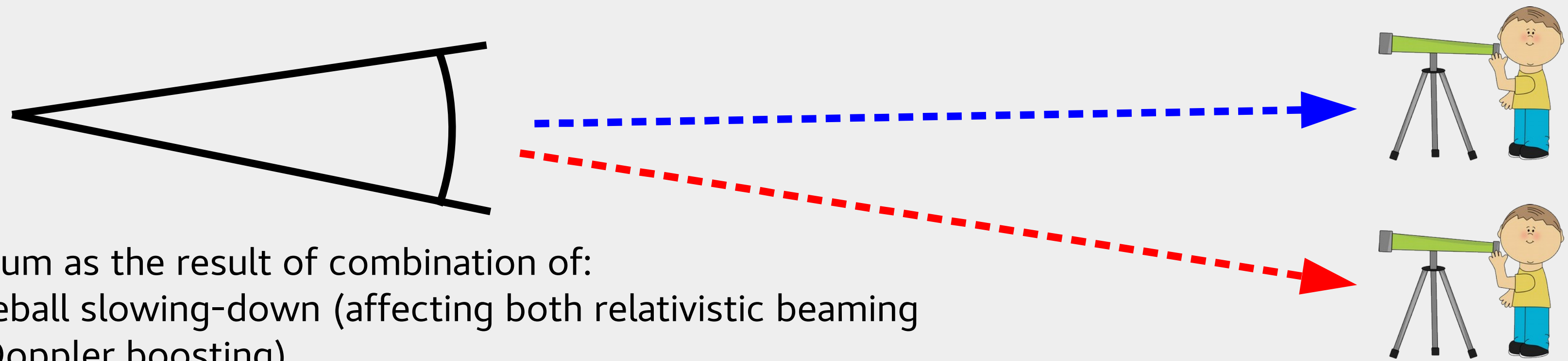
or the two combined



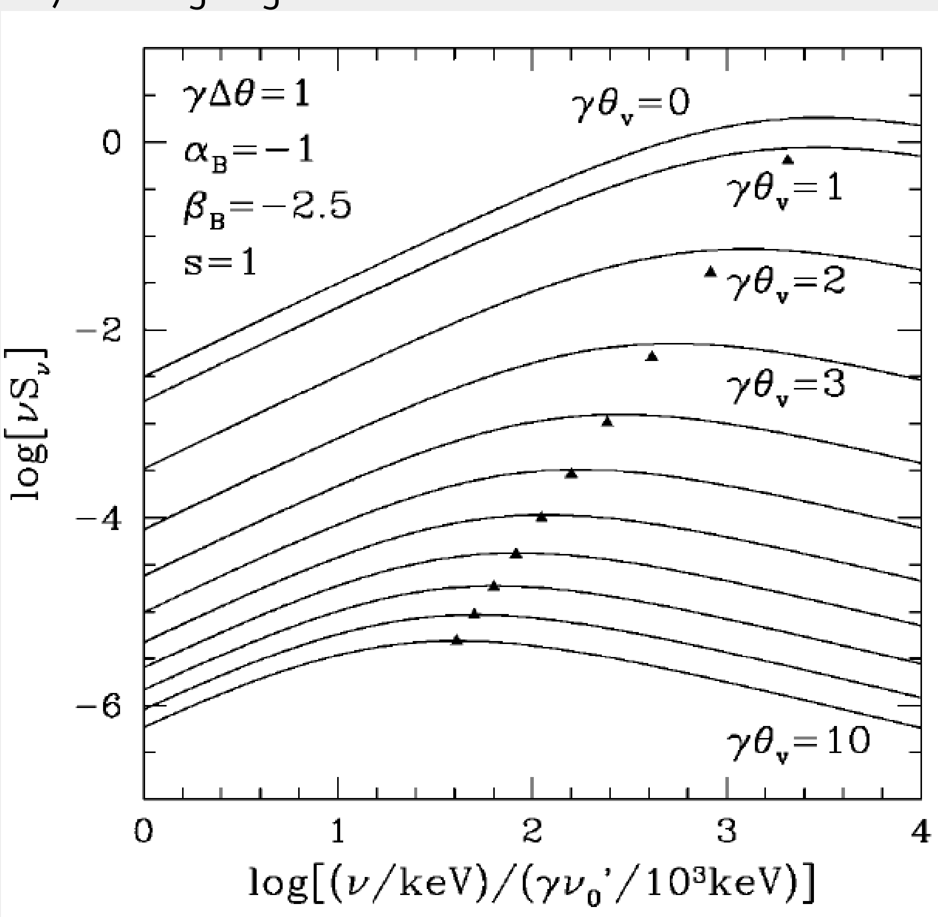


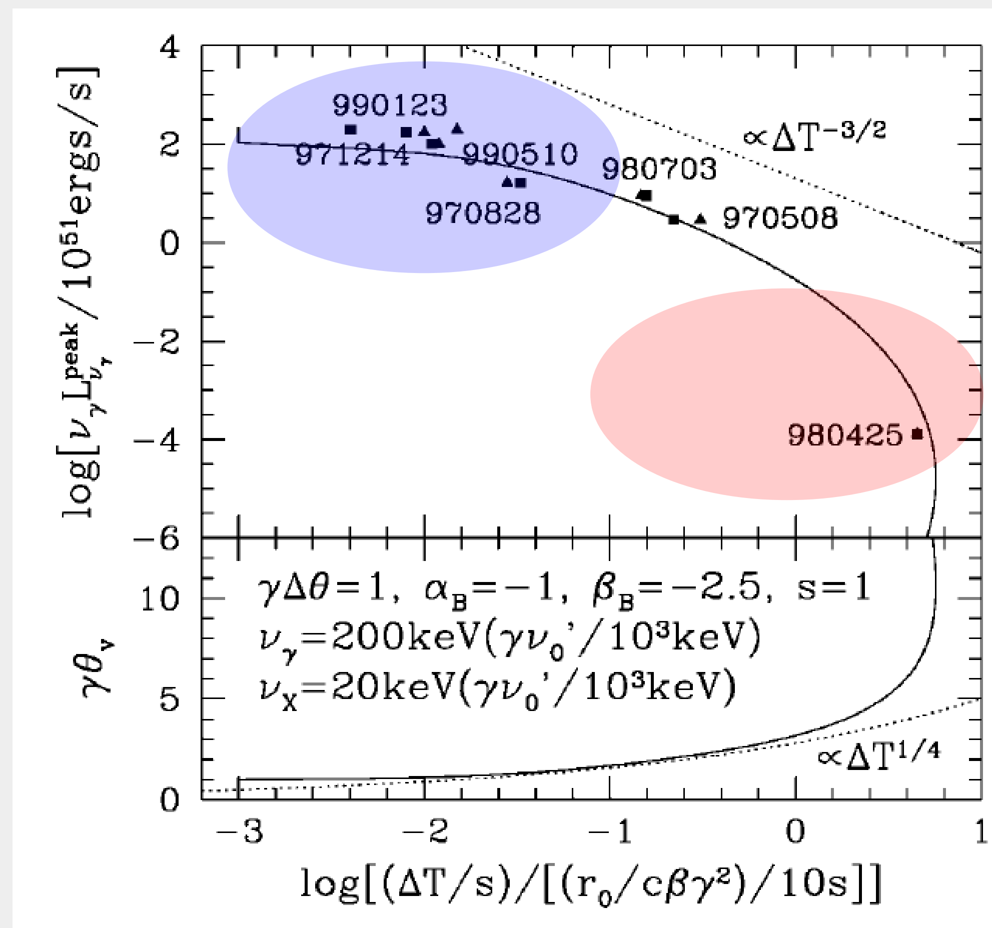
Ukwatta+ (2011)

Possible connection with jet/viewing angle



Lag-Lum as the result of combination of:
1) fireball slowing-down (affecting both relativistic beaming and Doppler boosting)
2) viewing angle





Ioka & Nakamura (2001)