Time variability in GRBs

Cristiano Guidorzi

University of Ferrara

HERMES SP

SCIENTIFIC WORKSHOP

18 - 19 NOV. 2020

What do GRB light curves look like?

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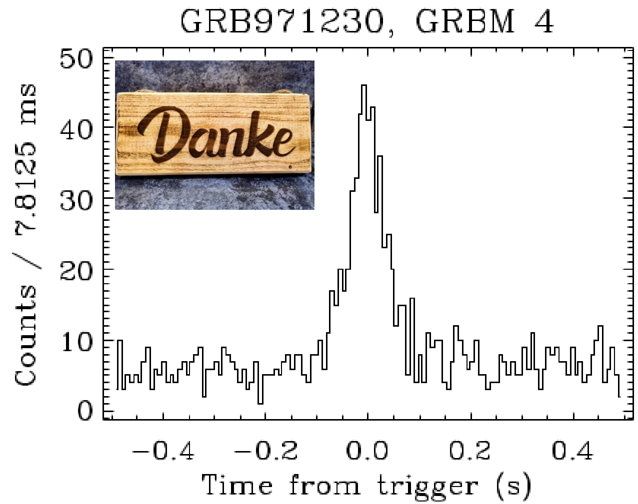
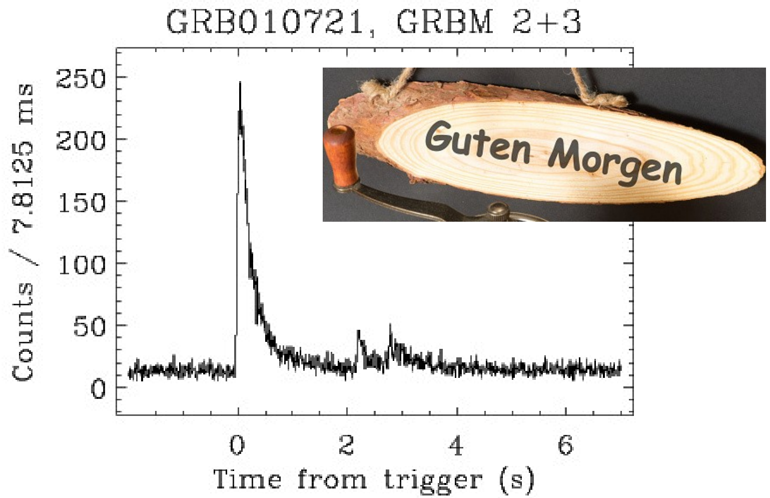
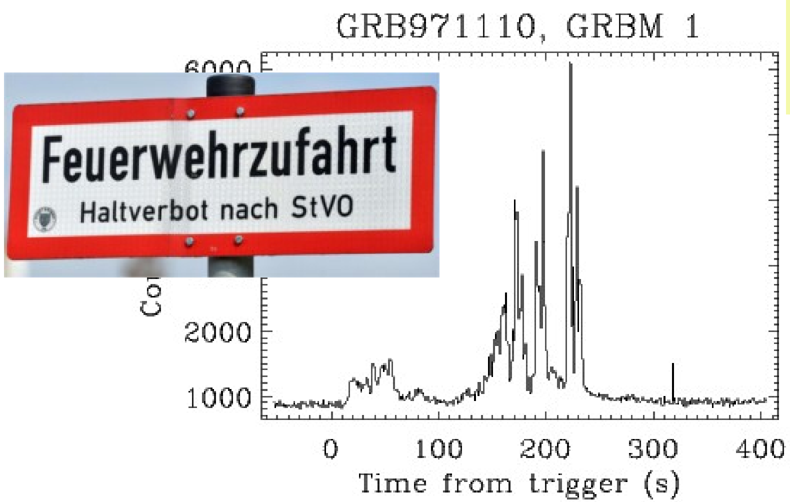
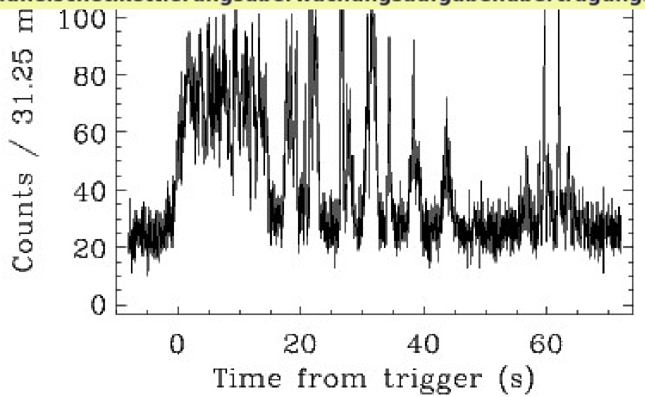






Rindfleischetikettierungsüberwachungsaufgabenübertragungsgesetz

Das **Rindfleischetikettierungsüberwachungsaufgabenübertragungsgesetz** (*RflEttÜAÜG*) war im Jahre 1999



From the BeppoSAX (1996-2002) GRBM Catalogue of GRBs

What do GRB light curves look like?

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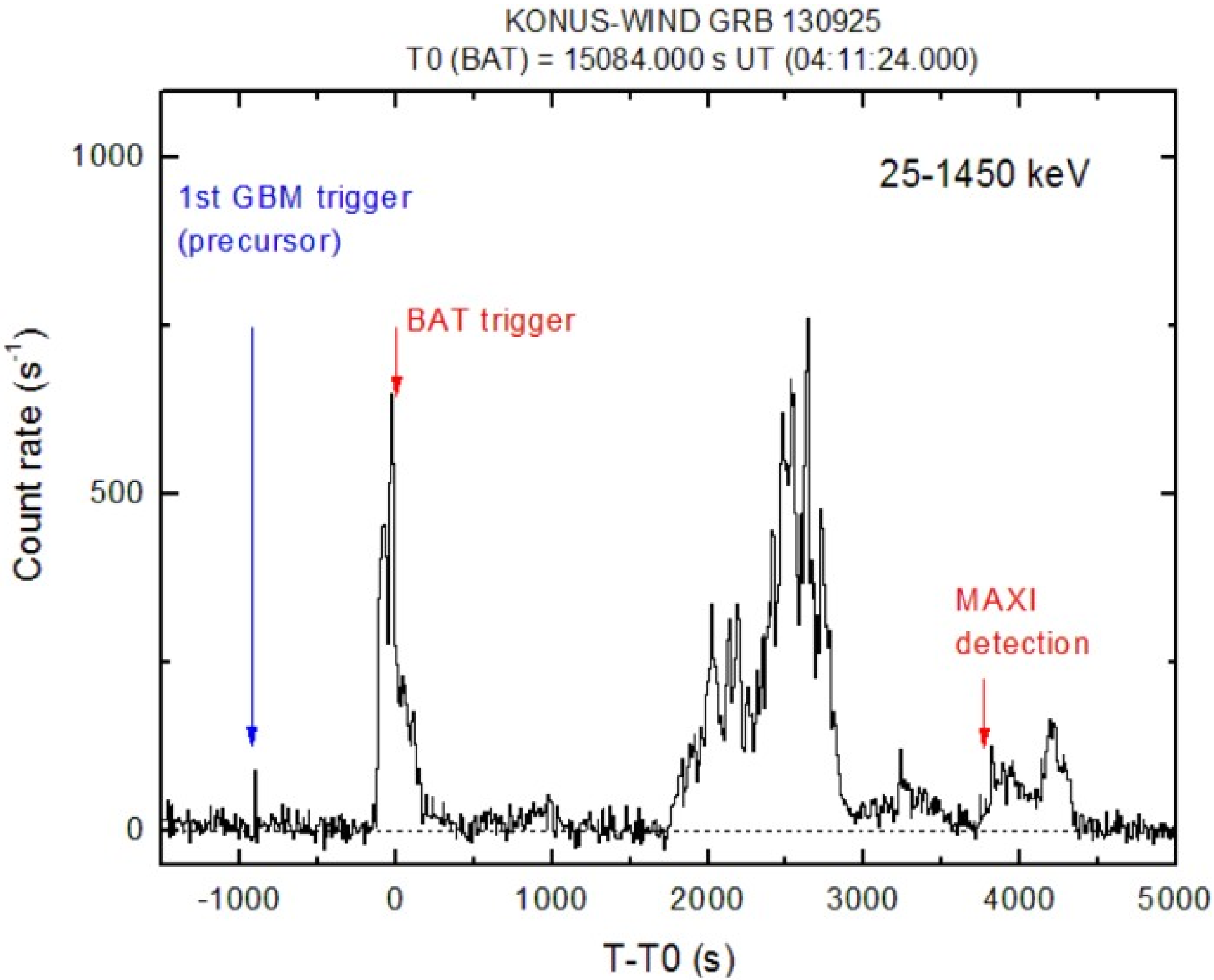
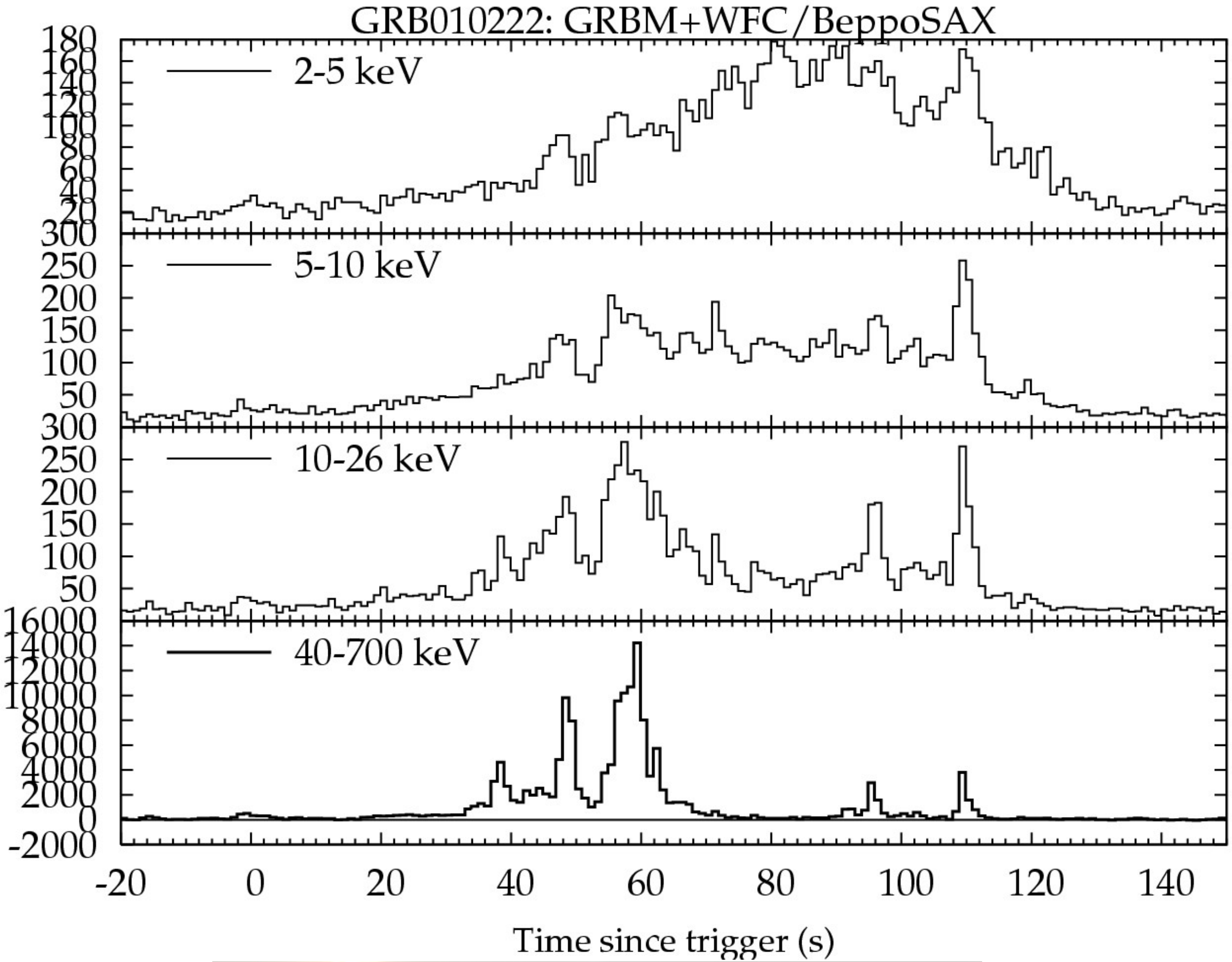
…and rarely so-called “ultra-long”



(Frederiks+19)

GRB profiles: X- to gamma-rays

Energy



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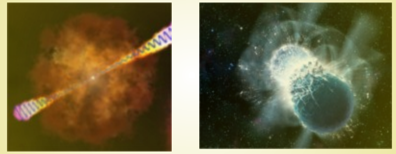
Progenitors



Physics

Released energy

Peak energy of nuFnu

Radiative process(es)

Luminosity

...

Size of emitting region

Bulk Lorentz factor

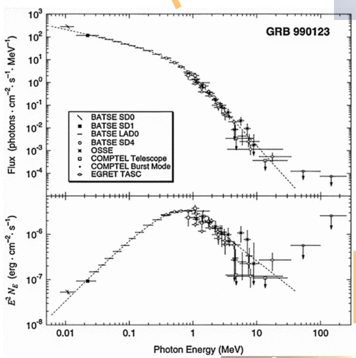
Inner engine activity

Jet propagation

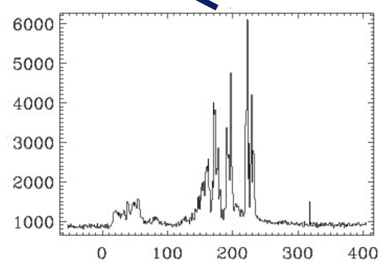
Dissipation mechanism(s)

?

Observables

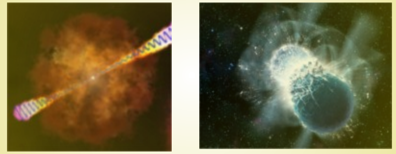


Energy spectrum



Time profiles

Progenitors



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Muto ergo sum

Deciphering Variability

Duration

Variability Metrics

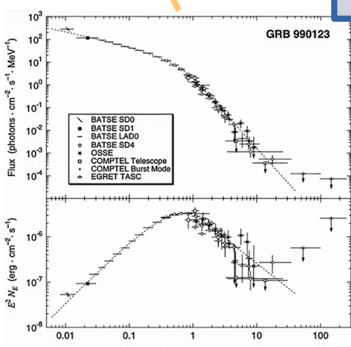
Variance Decomposition

Minimum Variability Timescale

Stochastic Process

all vs. energy range

Observables



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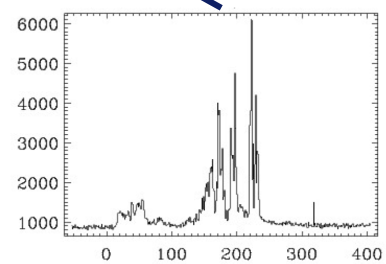

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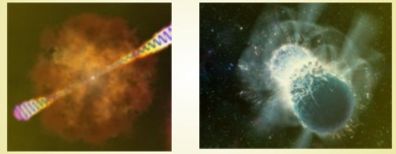

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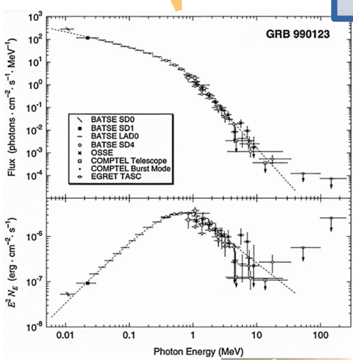

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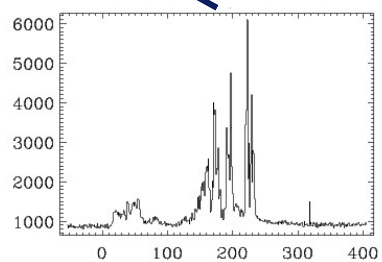

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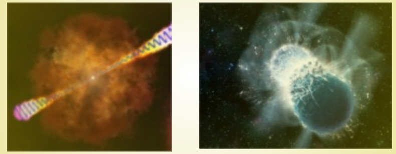
Progenitors



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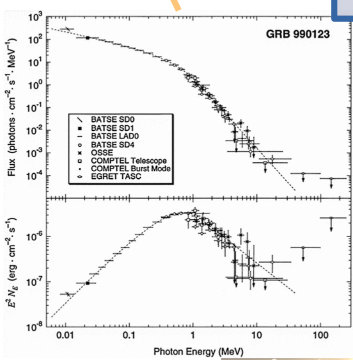
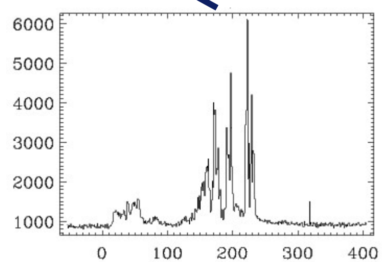
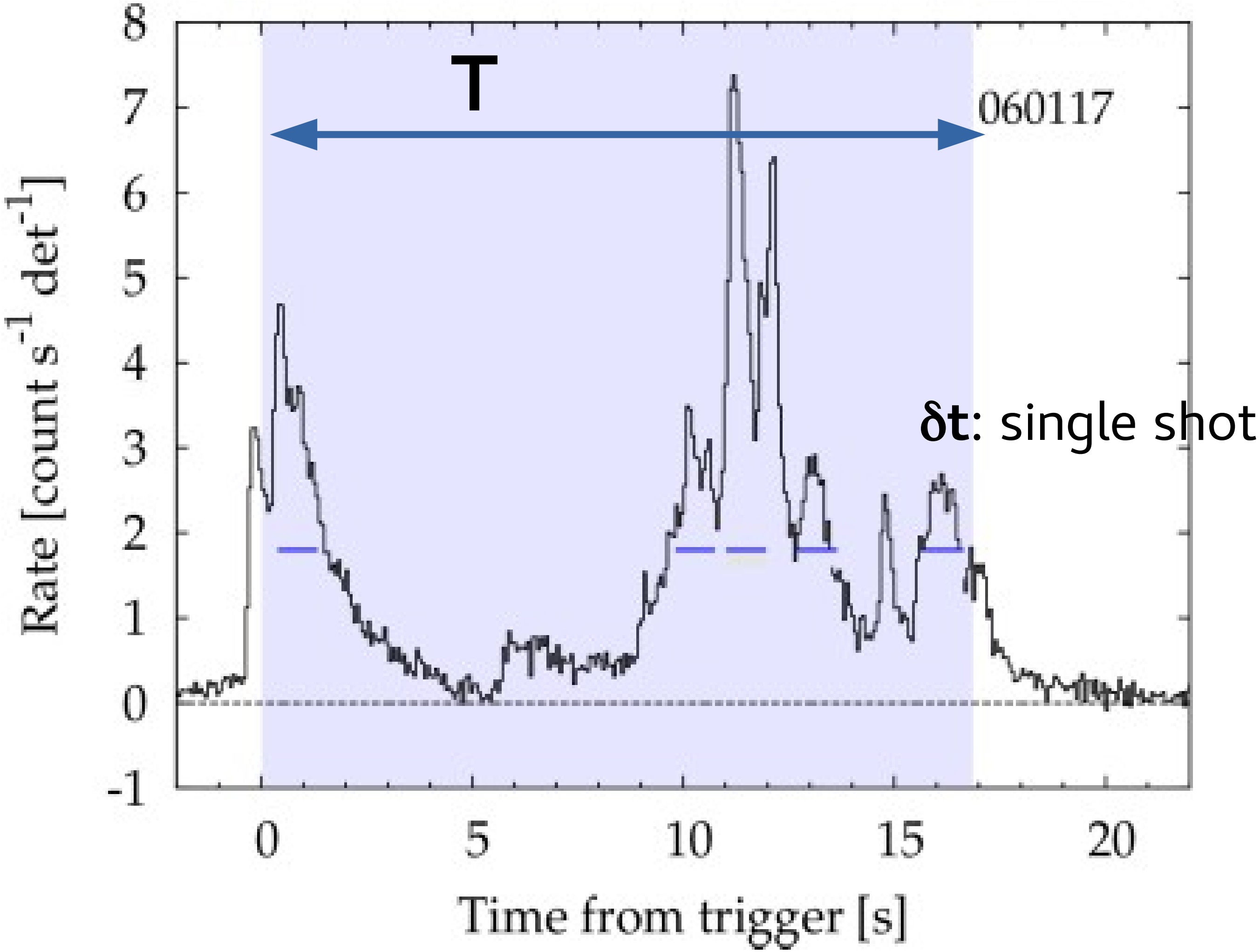


Energy spectrum



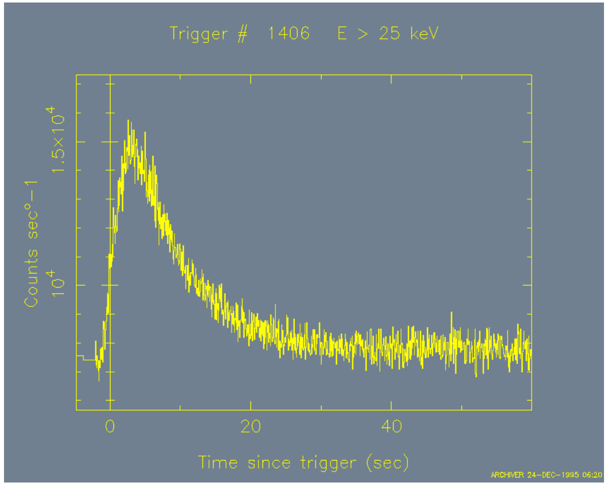
Time profiles

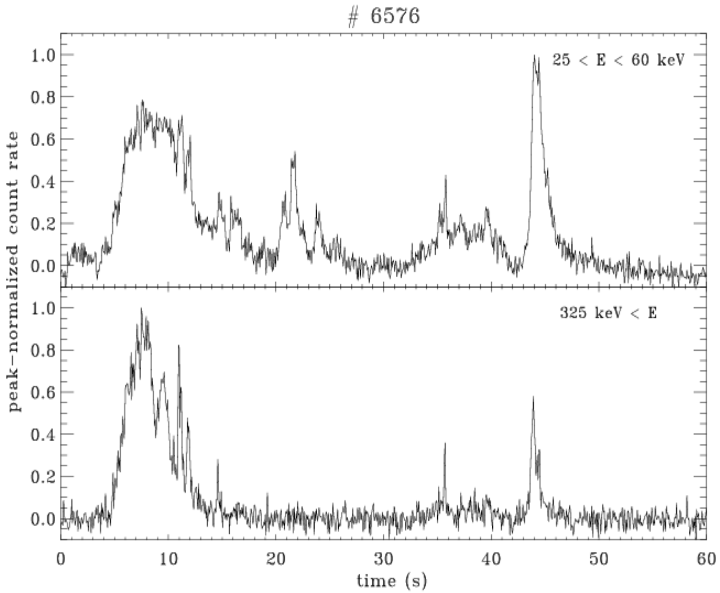
Variability: the simplest metrics T/δt

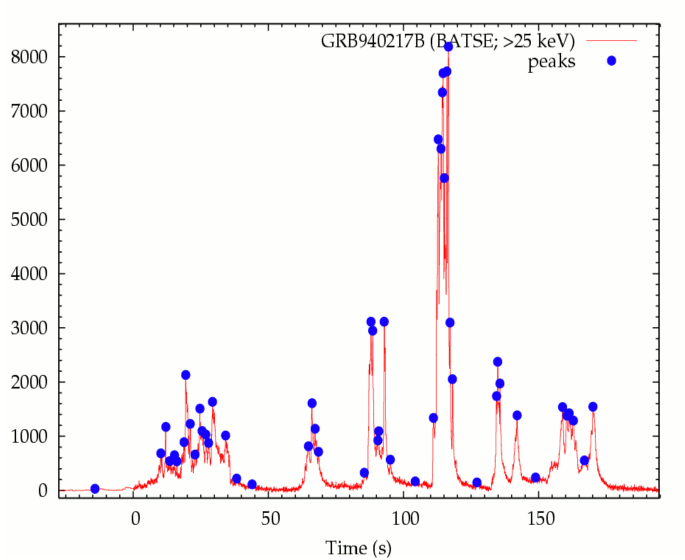


Different degrees of variability

- δt ~ T (1 single smooth pulse, e.g. FRED)
- δt < T (multi-peak burst)
- δt << T (high-frequency variability + long quiescent times)

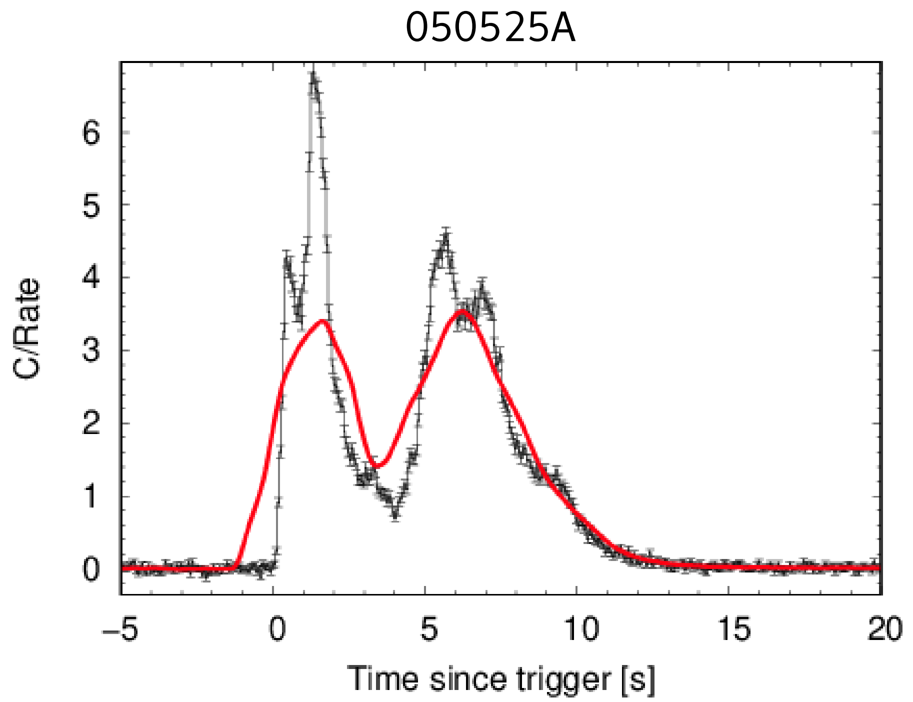






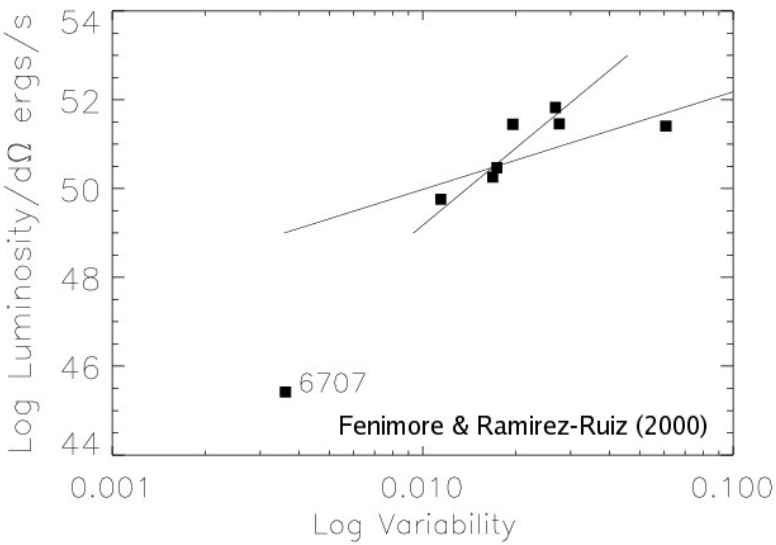
Variability: some metrics

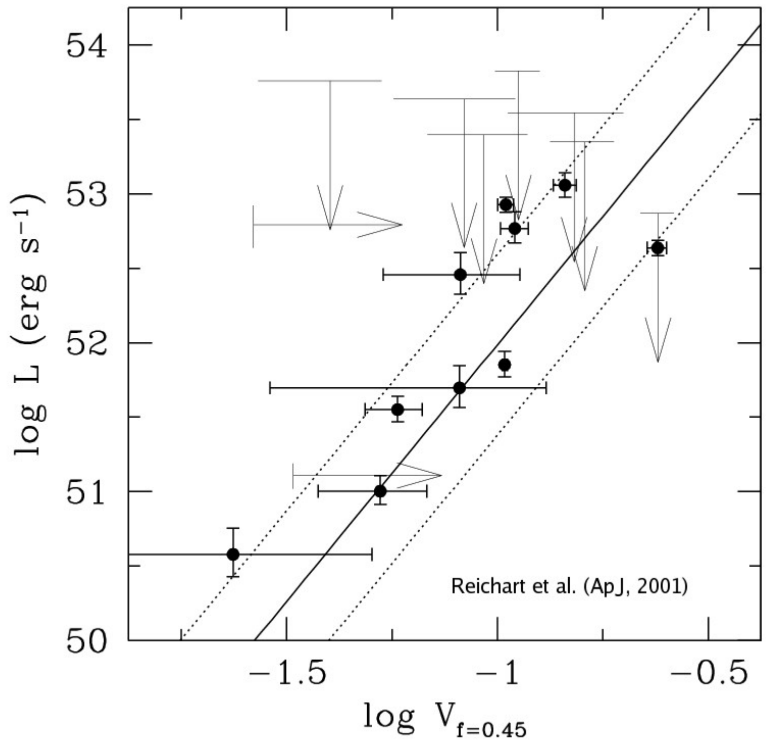
- Given a time profile uniformly binned: $\{c_i\}$ (i=1,...N)
- Determine a smoothed profile $\{g_i\}$ (through some low-pass filter), to be used as a reference one.
- Compute the variance of $\{c_i\}$ with respect to $\{g_i\}$
- Remove the statistical noise $\{v^2_{i,statnoise}\}$ due to counting statistics
- Normalise by a factor f_N



$$V \stackrel{\text{def}}{=} \frac{\sum_{i=1}^{N}\left[\left(c_i - g_i\right)^2 - v^2_{i,\text{statnoise}}\right]}{f_N}$$

Variability vs. Luminosity relation





$$V = Y^{-0.24} \frac{1}{N} \sum \frac{(C_i - < C >_{0.3T_{90}})^2 - (B_i + C_i)}{C_p^2}$$

$$V_f^E = \frac{\sum_{i=1}^{N} [(\sum_{j=1}^{N} a_{ij} C_j)^2 - \sum_{j=1}^{N} a_{ij}^2 C_j]}{\sum_{i=1}^{N} [(\sum_{j=1}^{N} b_{ij} C_j - B_i)^2 - \sum_{j=1}^{N} b_{ij}^2 C_j]},$$

Variability vs. Luminosity relation

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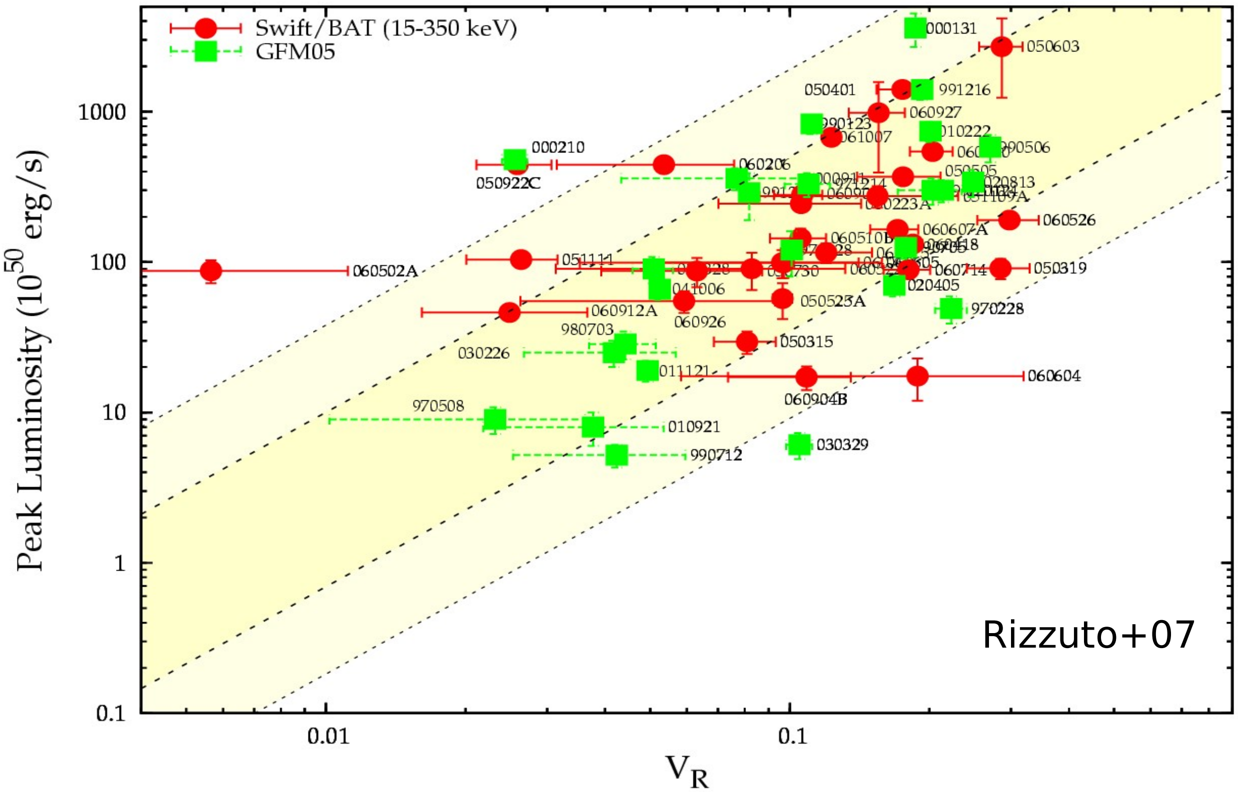
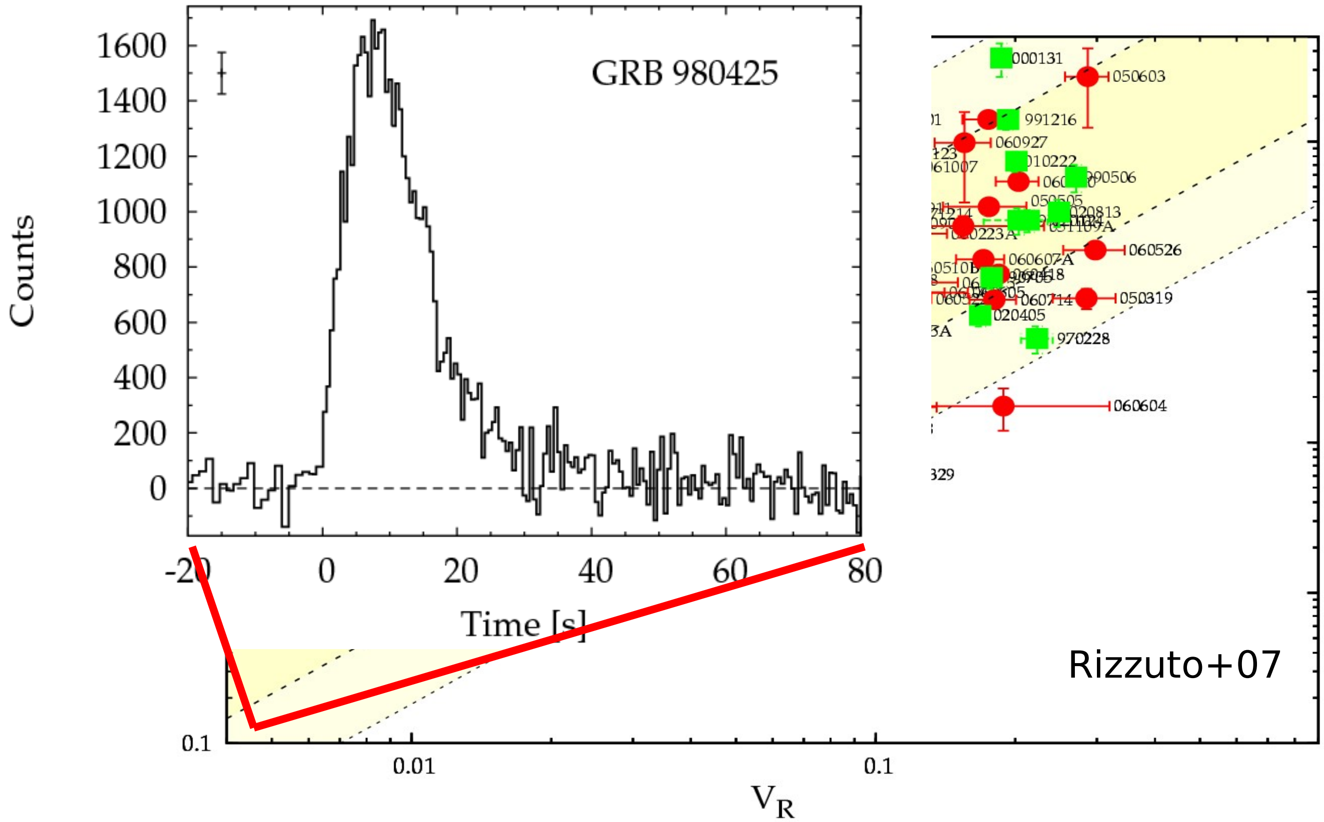


Significant Correlation, but highly scattered (=0.5-0.6 dex)

Variability vs. Luminosity relation



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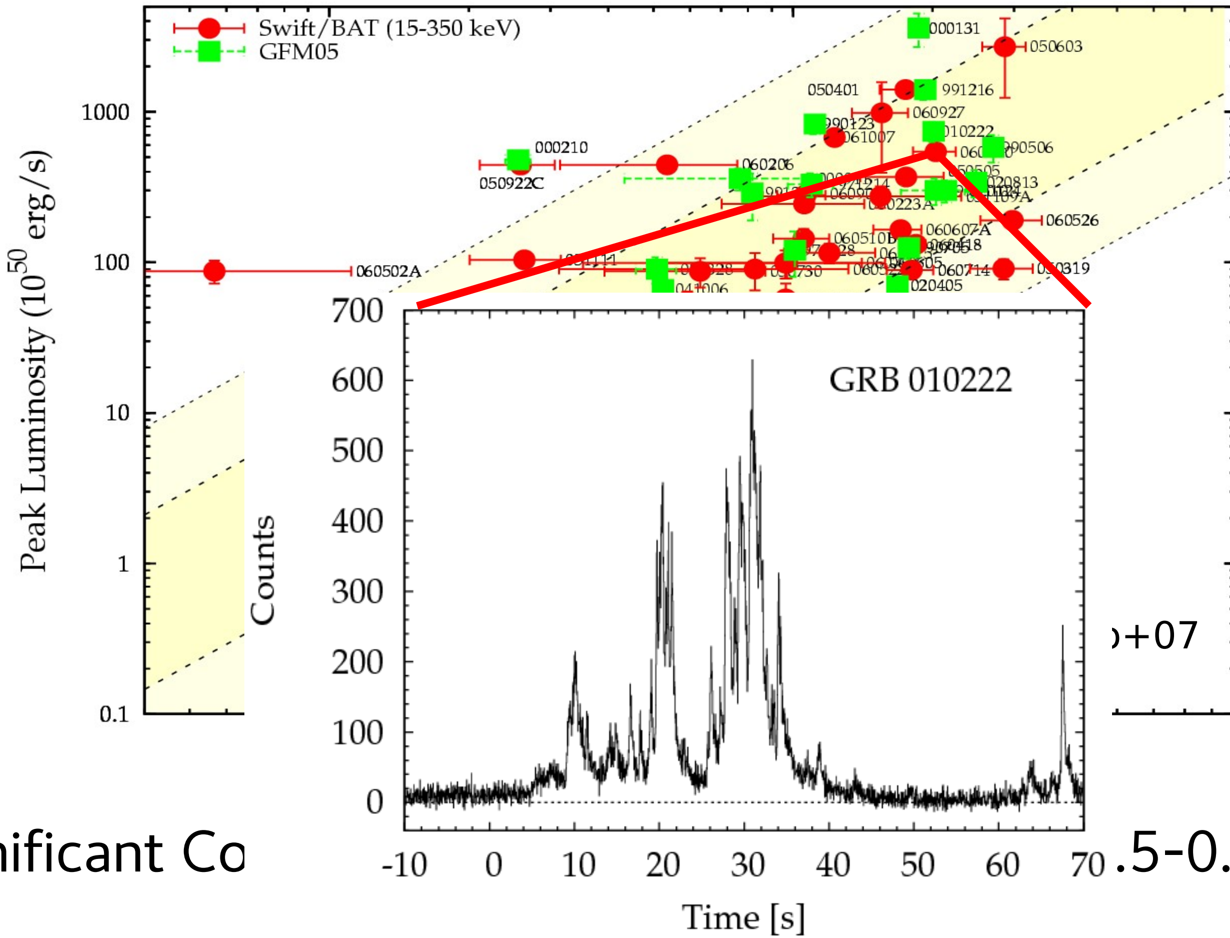
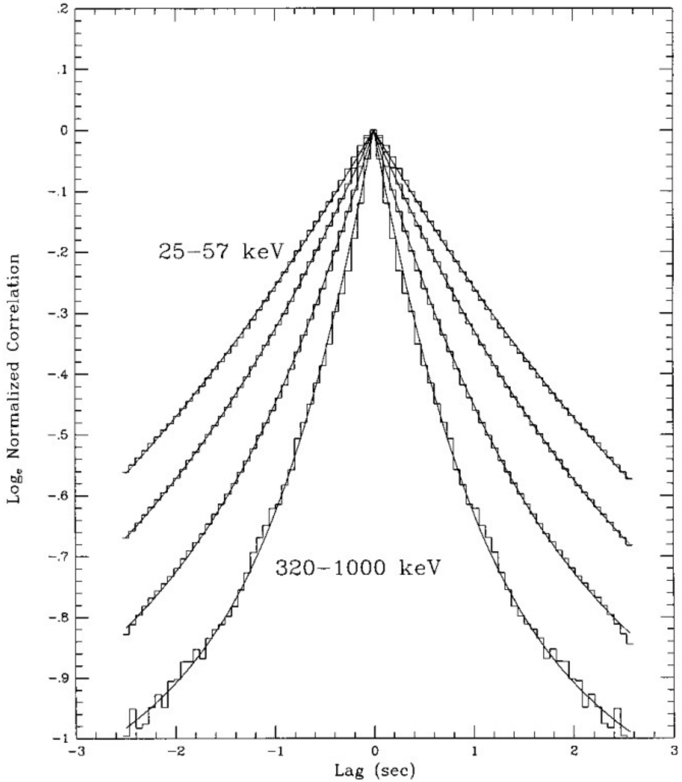


)+07

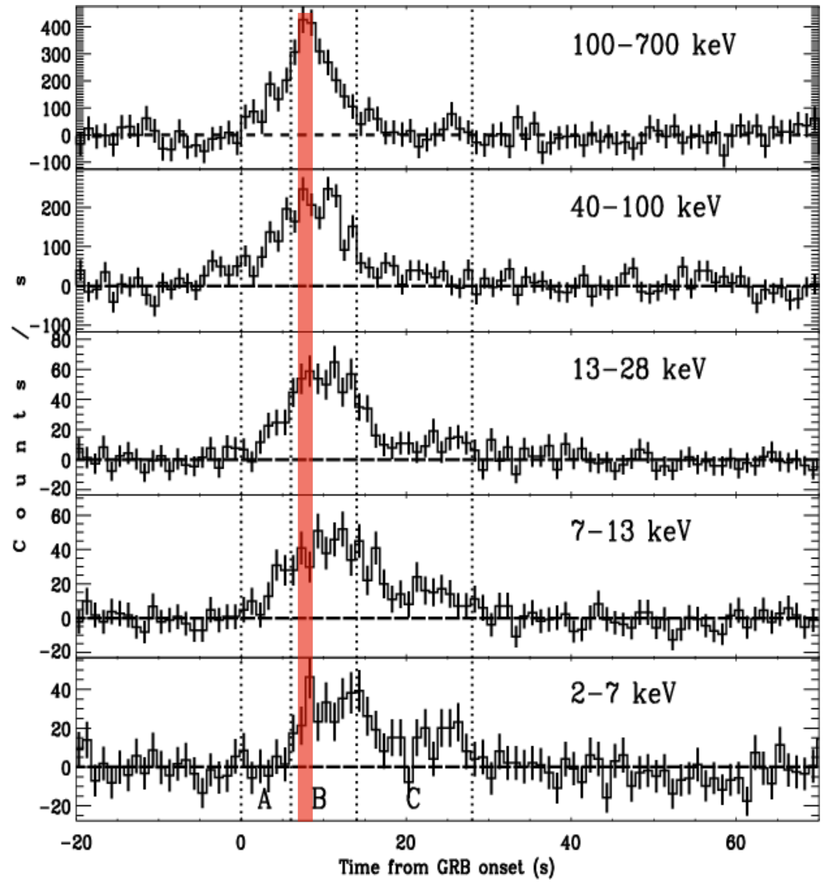
Significant Co .5-0.6 dex)

Pulse width vs. energy and spectral lag



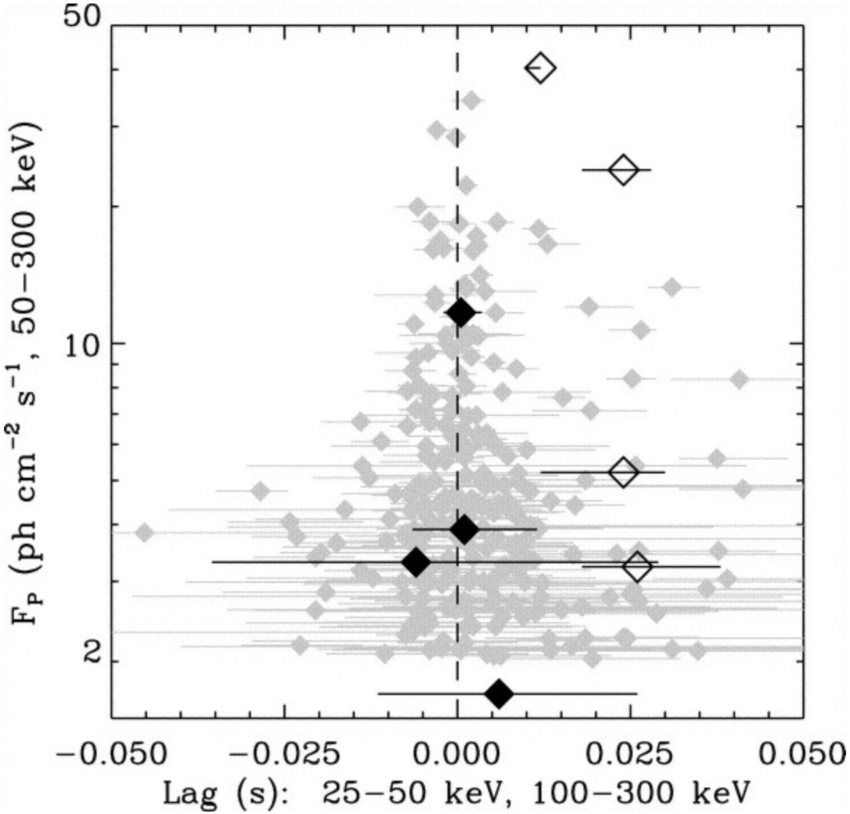
$$w(E) \propto E^{-0.4}$$

(Fenimore+95)

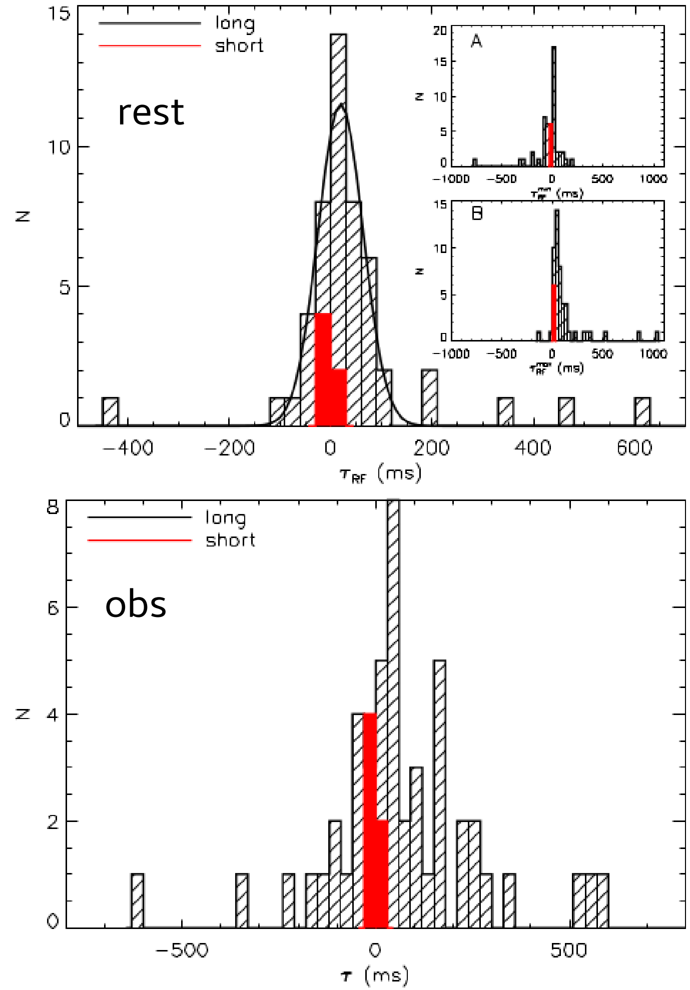


Example: GRB 010214 by BeppoSAX
(CG+03)

Spectral lag: short vs. long GRBs



Lag distribution of **short** GRBs
(Norris&Bonnell06)



Swift; 100-150 keV vs. 200-250 keV
(Bernardini+15)

Lag – Luminosity relation

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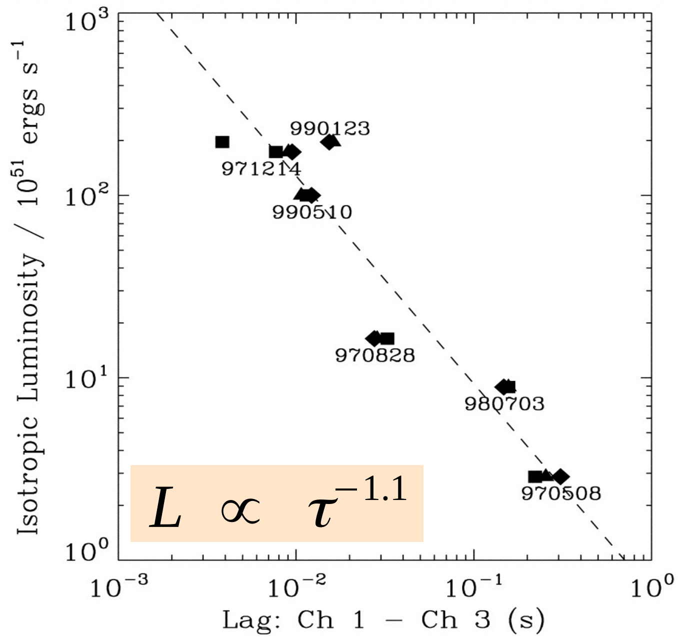
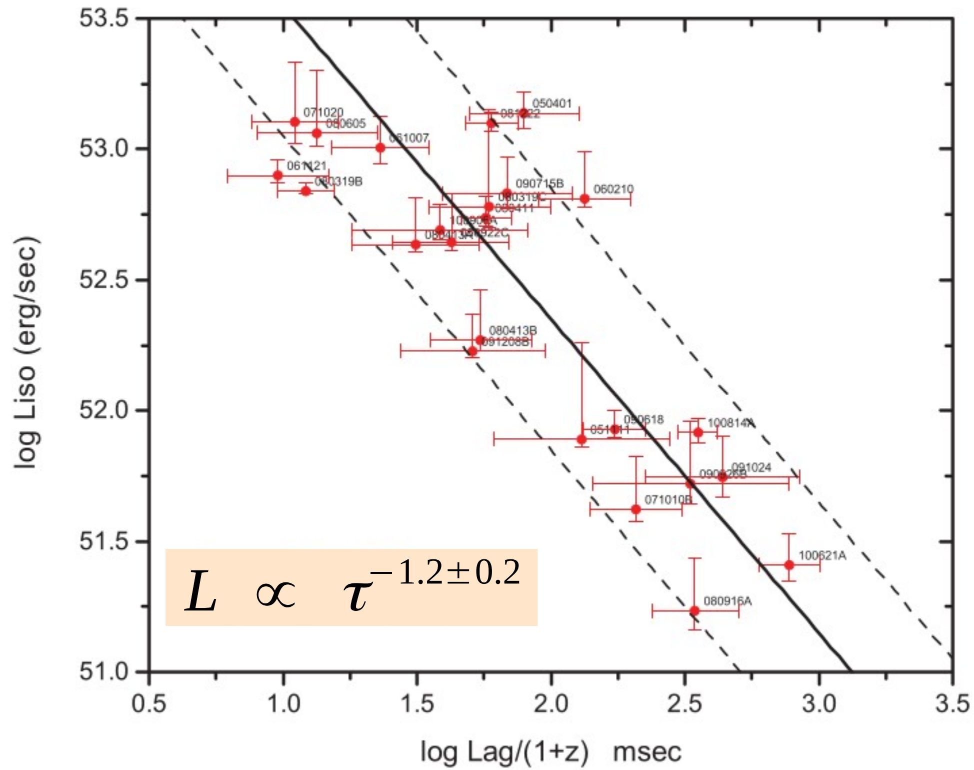


Discovered with a few BATSE GRBs with known z (Norris+00)



Confirmed by Swift/BAT GRBs with known z (Ukwatta+10)

Lag from CCF of rest-frame bands:
100-150 keV vs.
200-250 keV

Lag – Lum relation extends to X-ray flares

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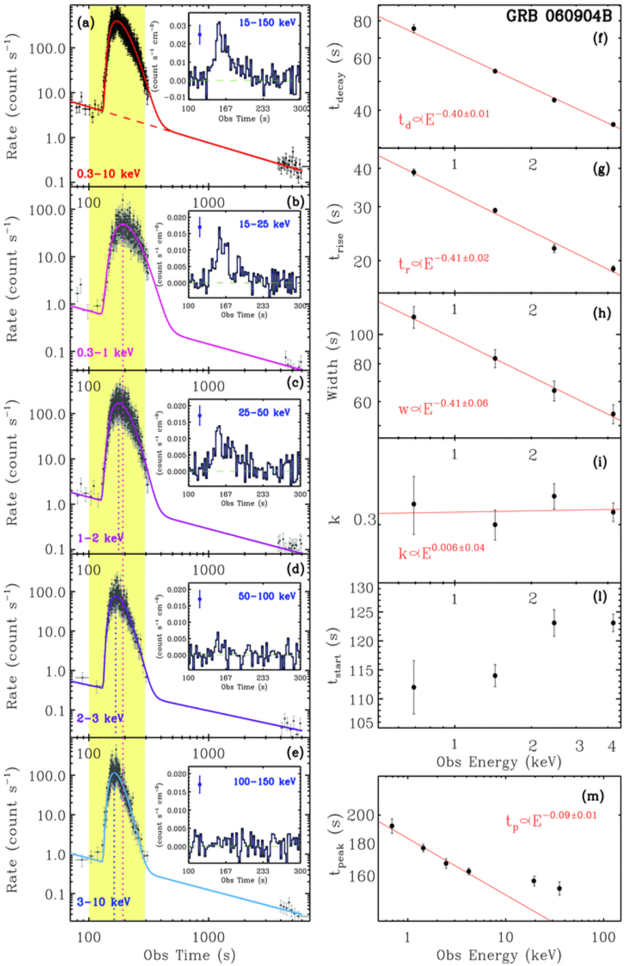
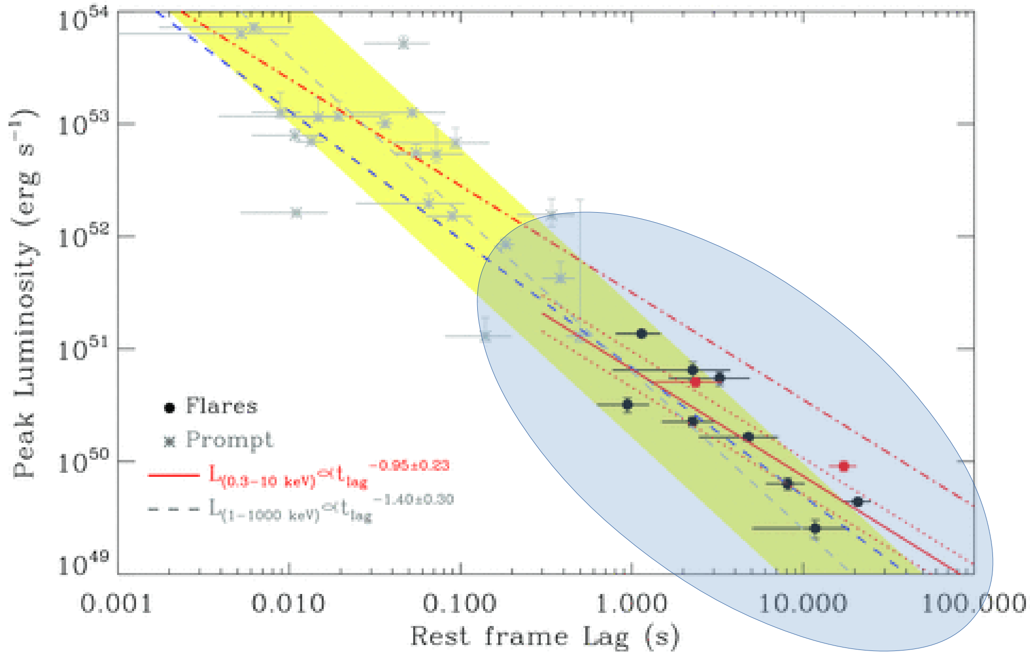




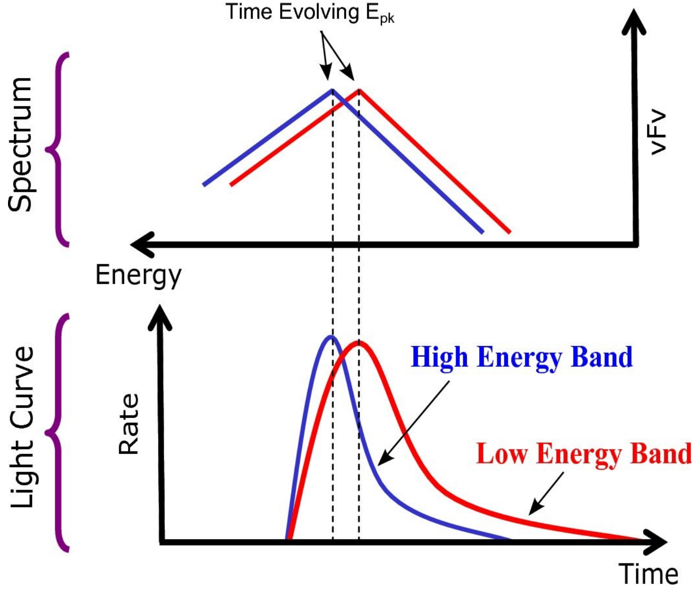
(Margutti+10)

X-ray flares do follow the same relation

$Log(L) \propto (-0.95 \pm 0.23)\ Log(\tau)$

Common mechanism for prompt gamma-rays and X-ray flares

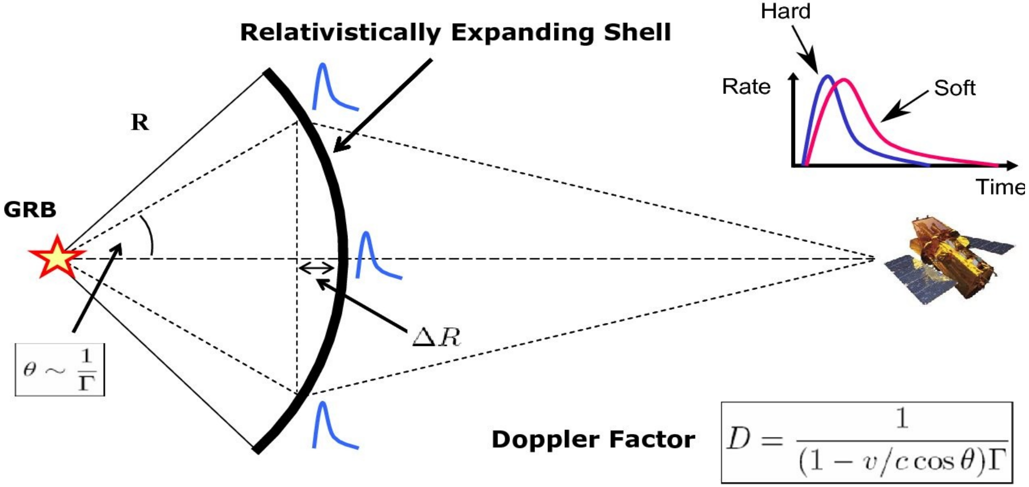
Lag – Lum: possible interpretations



(Dermer98; Kocevski & Liang03; Ryde05; Salmonson00; Ioka&Nakamura01; Dermer04)

- Intrinsic spectral evolution?
- Kinematic effect of curvature?
- Combination of both?

(Ukwatta+11)



Lag-Lum / Var-Lum : kinematic/geometric interpret.

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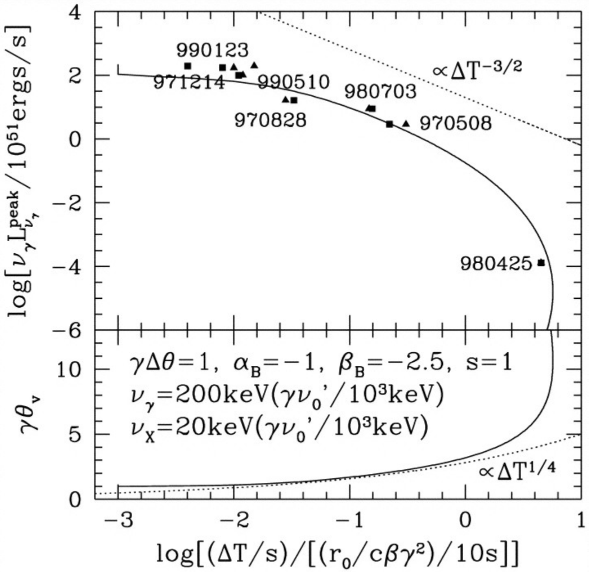
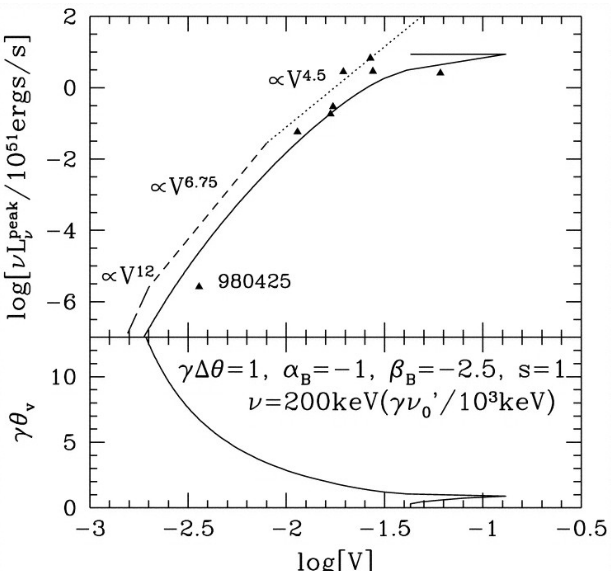
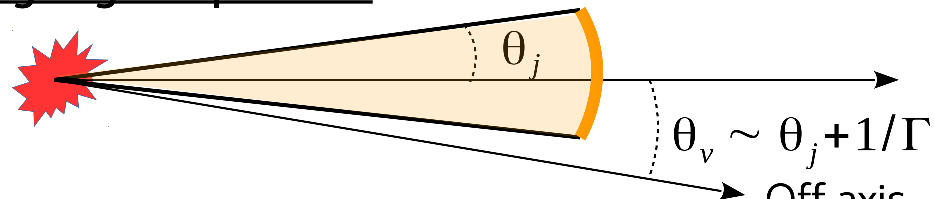




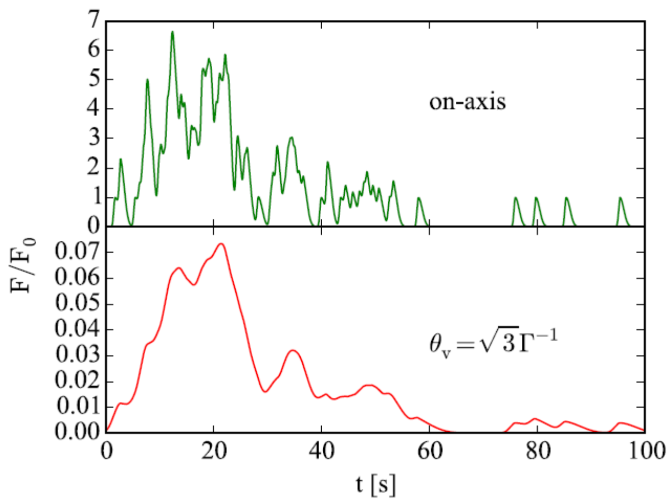
(Ioka & Nakamura 01)

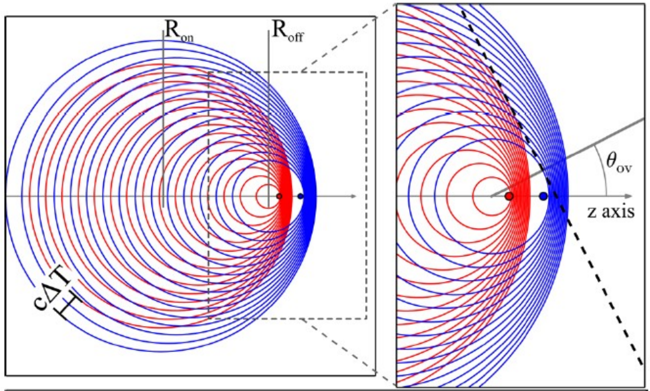
Viewing angle dependent

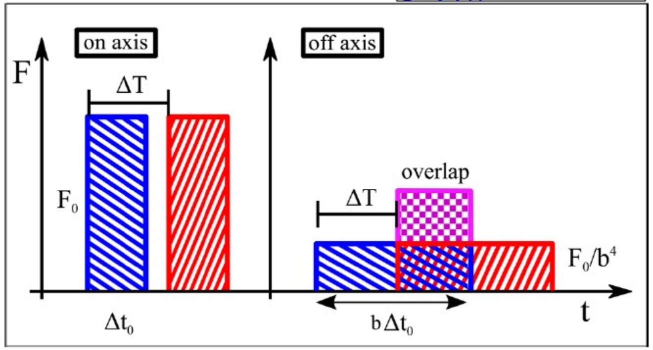


Off-axis view quenches high-freq variability (like a low-pass filter)

(Salafia+16)







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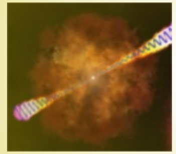

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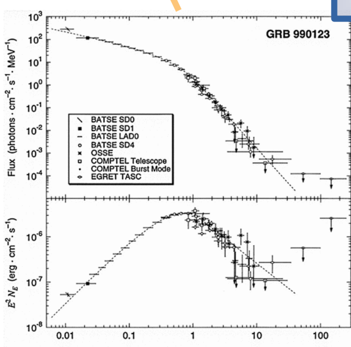
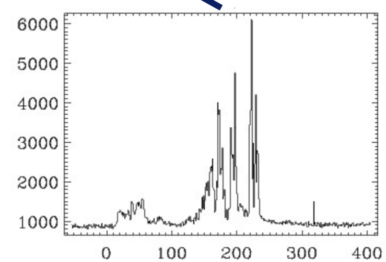


Energy spectrum



Time profiles

Power density in time domain

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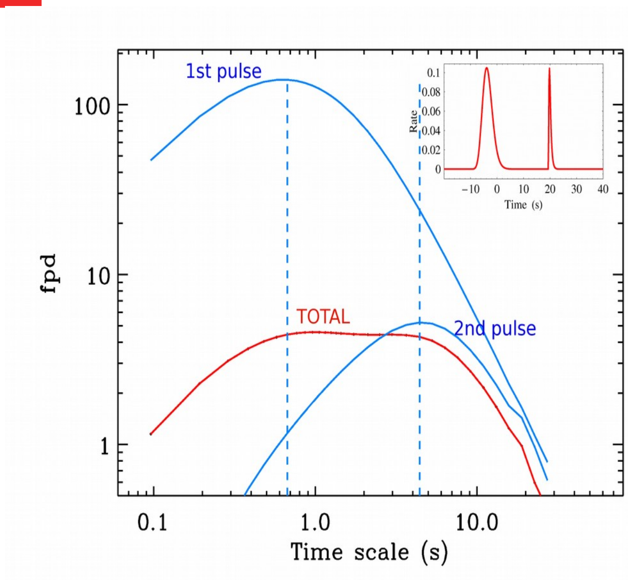
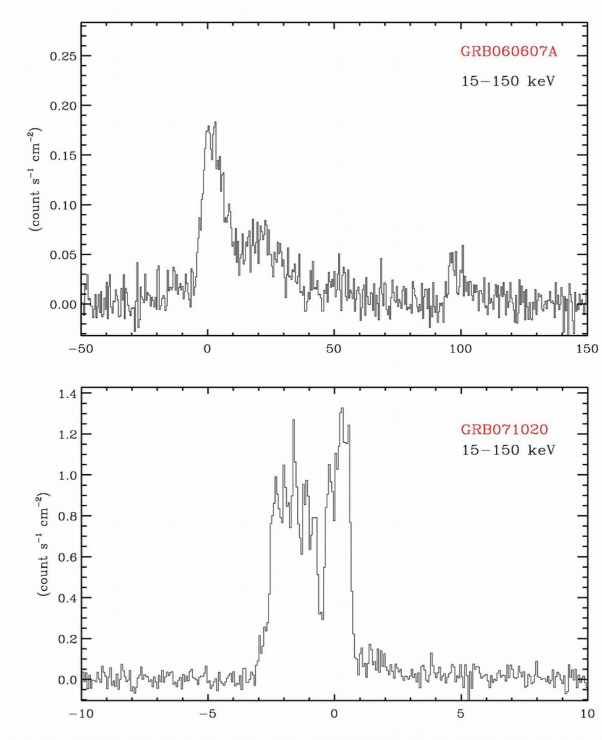
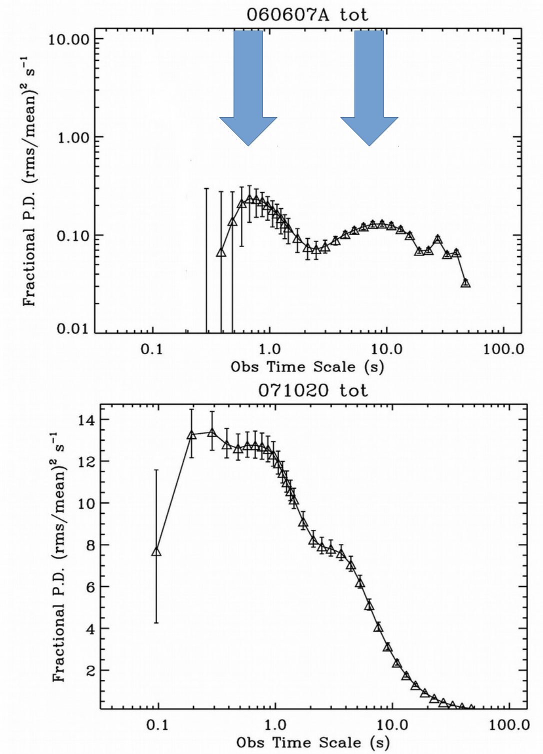


(Margutti PhD thesis 2009; T.P. Li 2001)





$$P(\Delta t) = \frac{Var(x)}{(\Delta t)^2} = \frac{\frac{1}{N}\sum_k (x(k) - \overline{x})^2}{(\Delta t)^2} = \frac{1}{N}\sum_k (r(k) - \overline{r})^2 \quad [\text{rms}^2]$$

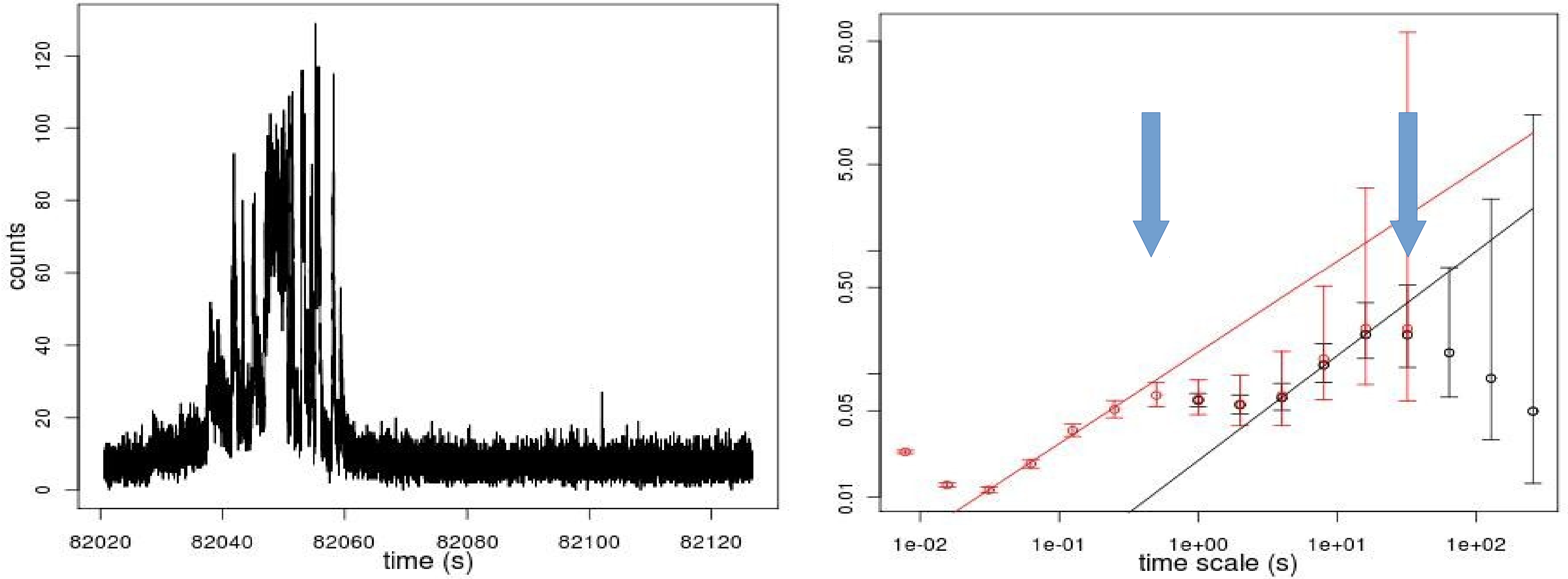
$$p(\Delta t) = \frac{dP(\Delta t)}{d\Delta t} \quad [\text{rms}^2\text{s}^{-1}]$$

$$fpd(\Delta t) = \frac{p_{\text{signal}}(\Delta t)}{r^2} \quad (\text{rms}/\text{mean})^2\text{s}^{-1}$$

Different characteristic time scales in the range 0.1 – 10 s

Wavelet power spectrum

GRB 980203 (BeppoSAX-GRBM)



(V. Esposito, master thesis, U. Ferrara)

- Light Curve decomposition based on MODWT (Maximum Overlap Discrete Wavelet Transform; Percival & Walden, 2006)
- Superposition of $\sim 10^{-1}$ s and ~10 s timescales in some GRBs

Dominant timescales from Fourier PDS

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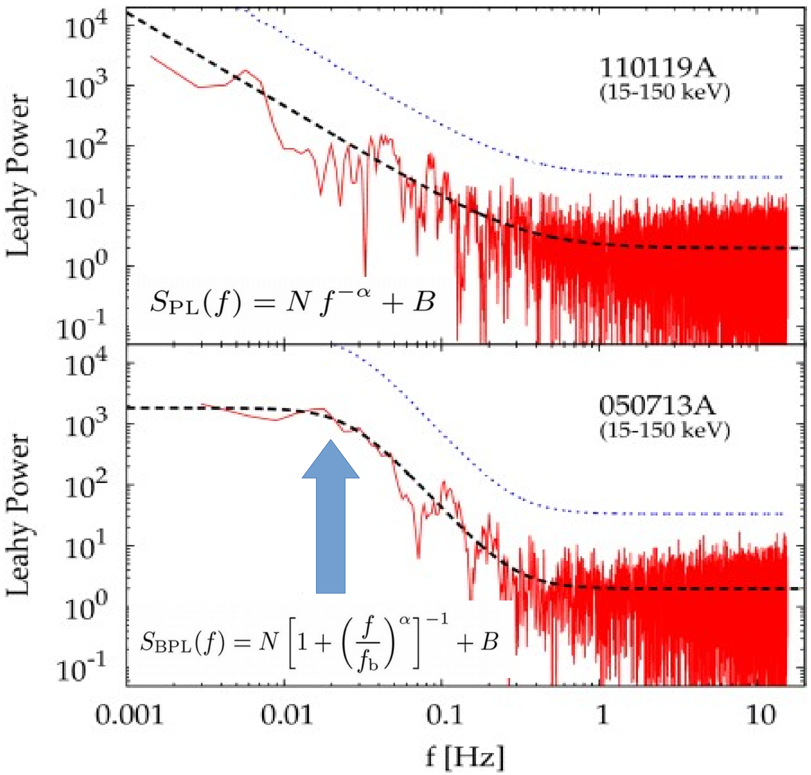
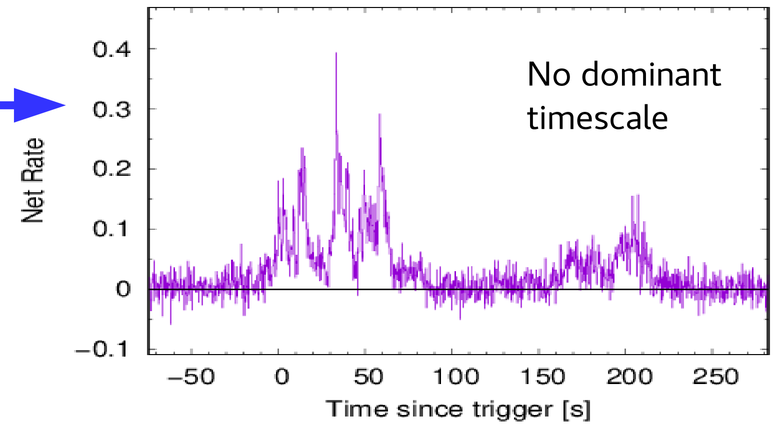
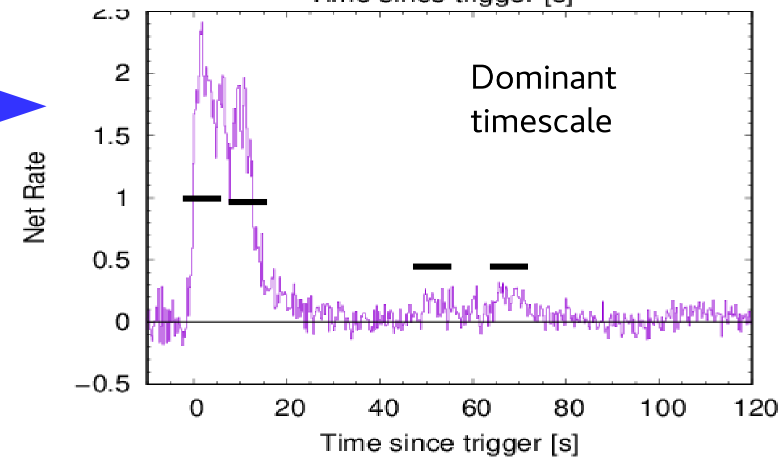




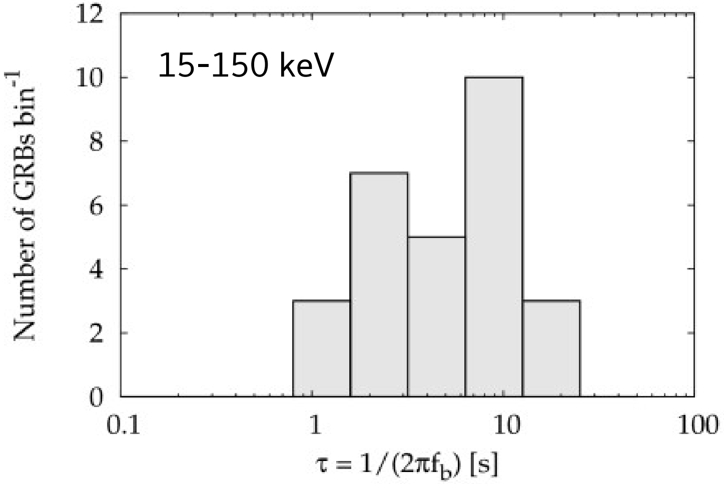


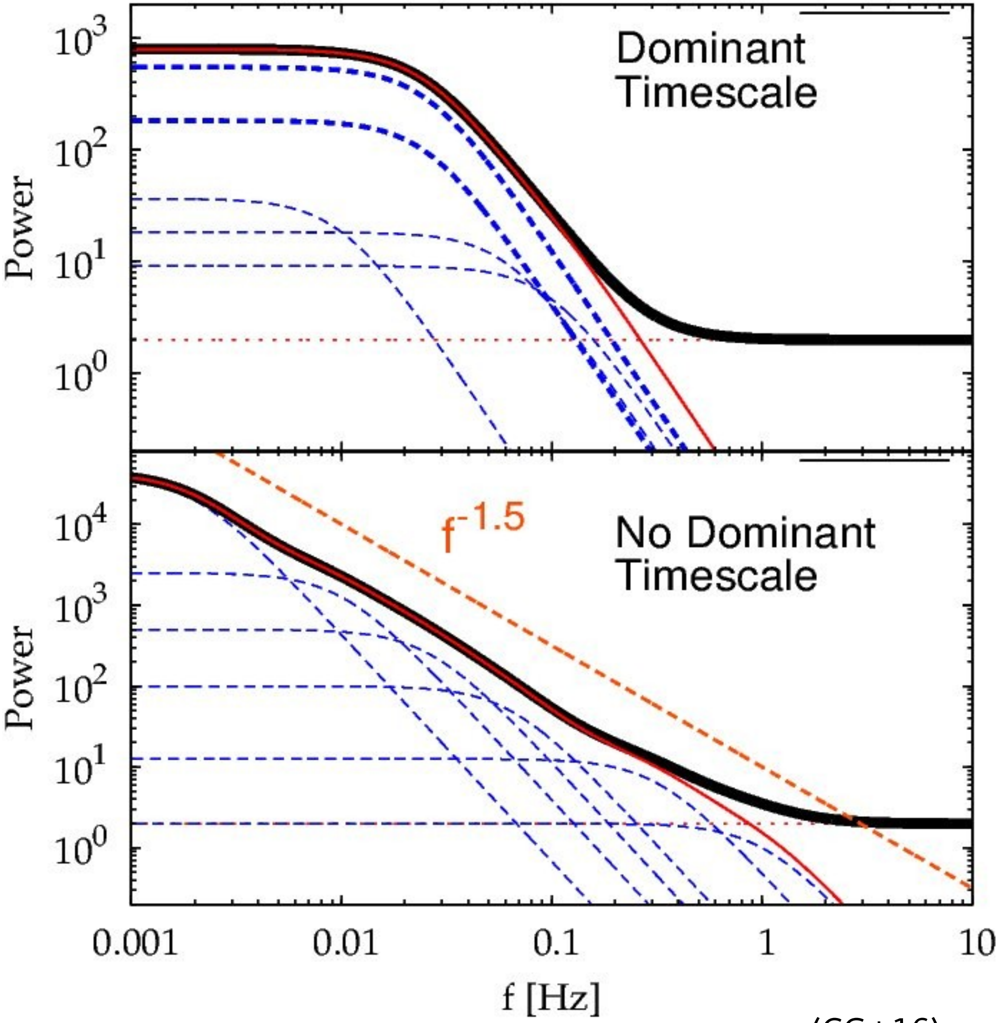
$$f_b = \frac{1}{2\pi\tau}$$

$$f_b = 0.021 \ \text{Hz}$$
$$\tau = 7.7 \ \text{s}$$

(CG+16)

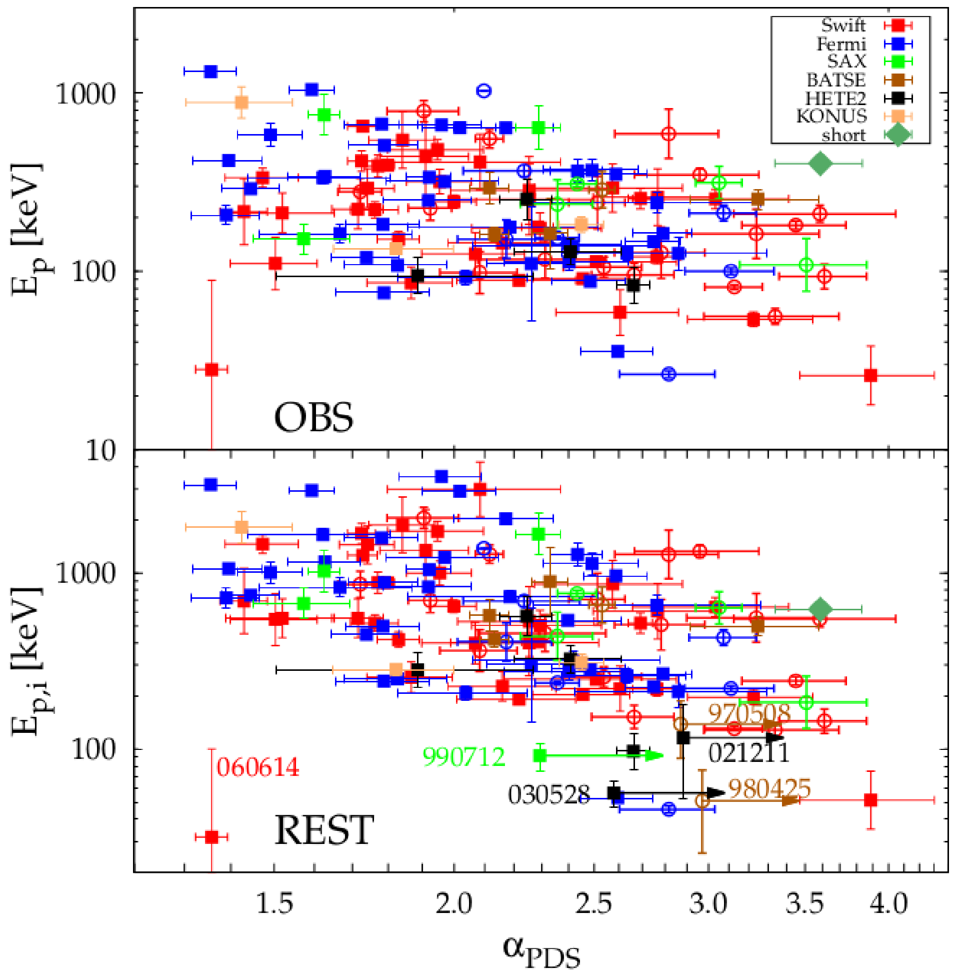
Fourier analysis of individual GRBs

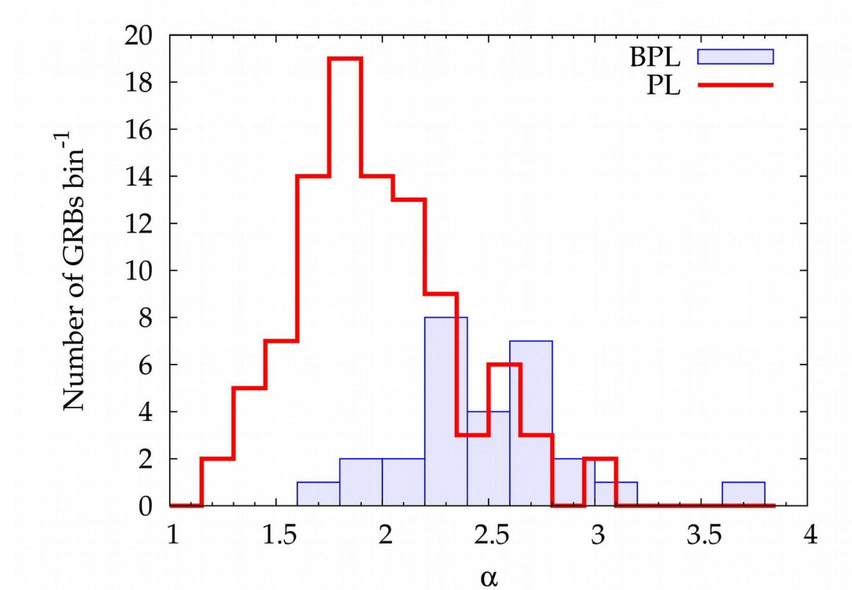




(CG+16)

PDS PL index correlates with Ep





It clashes with IS synchrotron prediction: $E_{p,i} \propto \Gamma^{-2}$

(Zhang & Mészáros02)

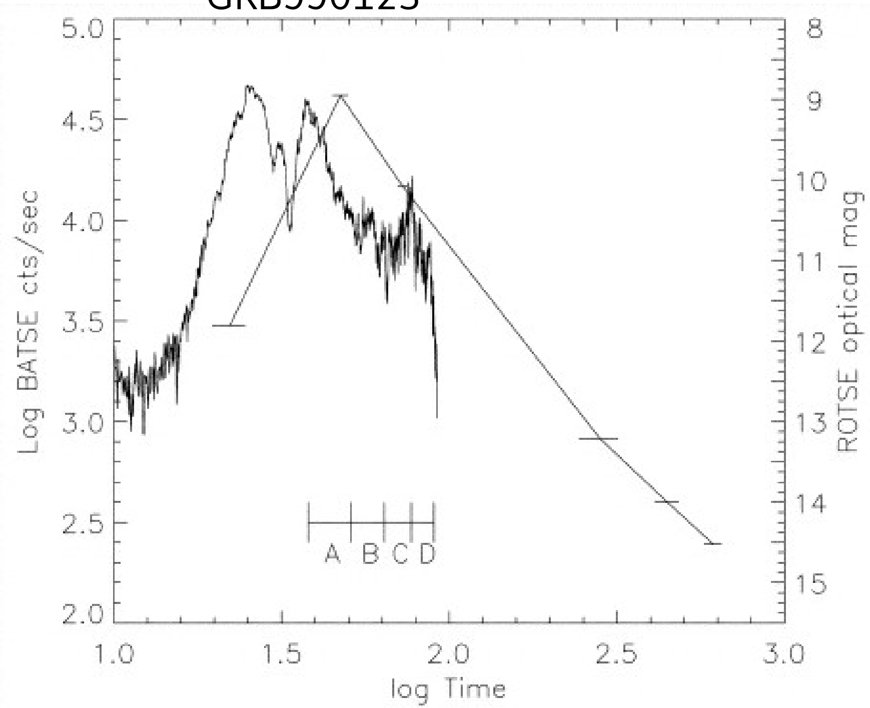
..unless structured jets with variable $\varepsilon_B=\varepsilon_B(\Gamma)$ and $\varepsilon_e=\varepsilon_e(\Gamma)$ are considered.

(Ramirez-Ruiz & Lloyd-Ronning02)

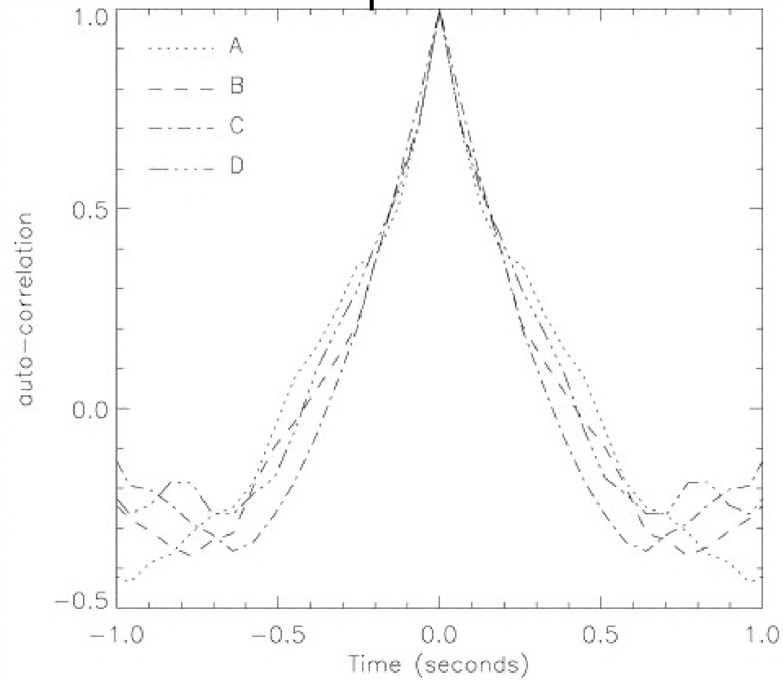
(Dichiara+16; CG+16)

Lack of evolution of pulse width

GRB990123



ACF of pulses

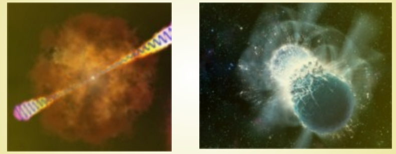


Should γ-rays be due to blastwave interaction with external medium, pulse width should increase with time.

→ dissipation must take place at the same distance.

(Fenimore+99)

Progenitors



Physics

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...

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Minimum Variability Timescale

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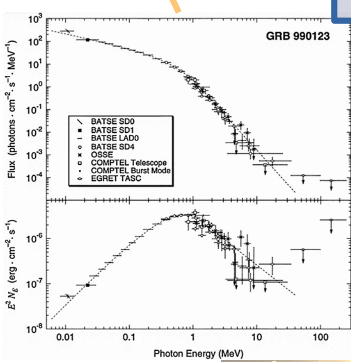
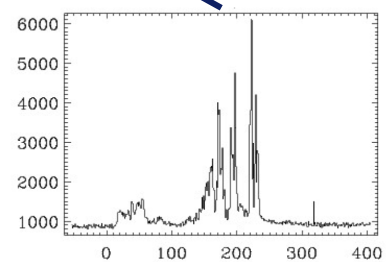


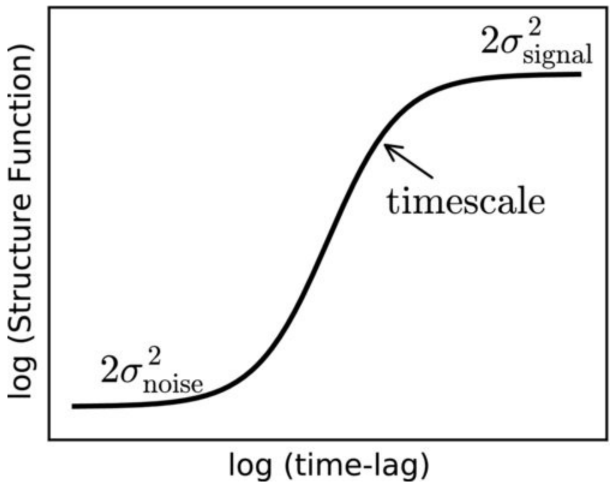
Energy spectrum



Time profiles

Minimum variability timescale: Haar wavelets

University of Ferrara

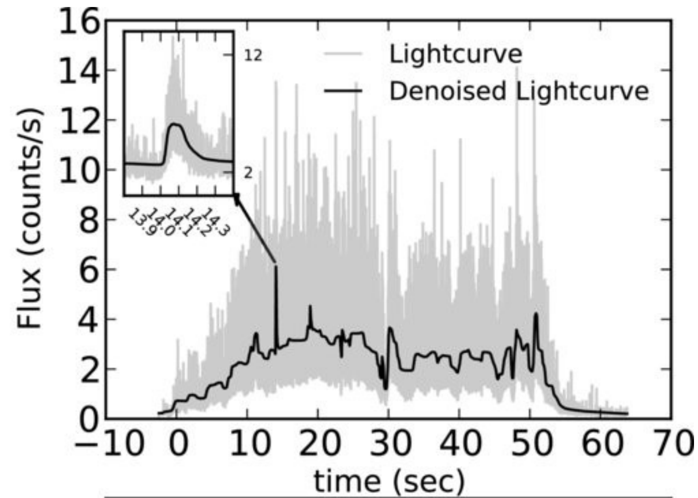


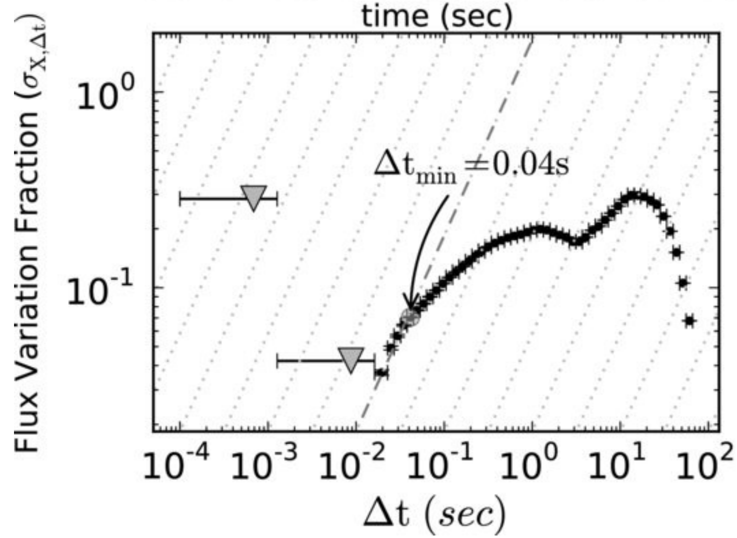
$$SF(\tau) = \langle [X(t) - X(t+\tau)]^2 \rangle$$

$$\bar{X} = \frac{1}{\tau} \sum_{n=0}^{\tau-1} X_{t-n}$$

Allan variance: $\sigma_X^2(\tau) = \frac{1}{2} \langle [\bar{X}_t(\tau) - \bar{X}_{t-\tau}(\tau)]^2 \rangle$

$$\mathrm{var}\{d_{j,k}\} = \tau\, \sigma_X^2(\tau)$$





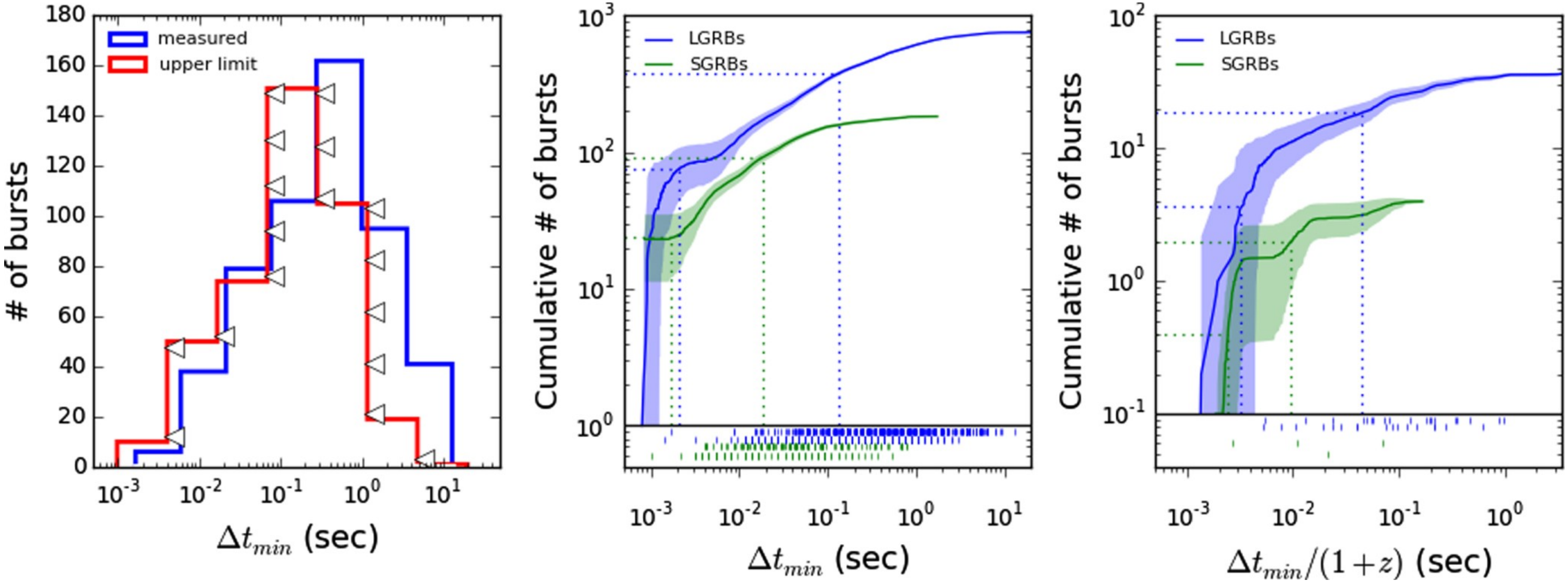
(Golkou+Butler14)

“Haar wavelet SF”

Minimum variability timescales (Fermi)

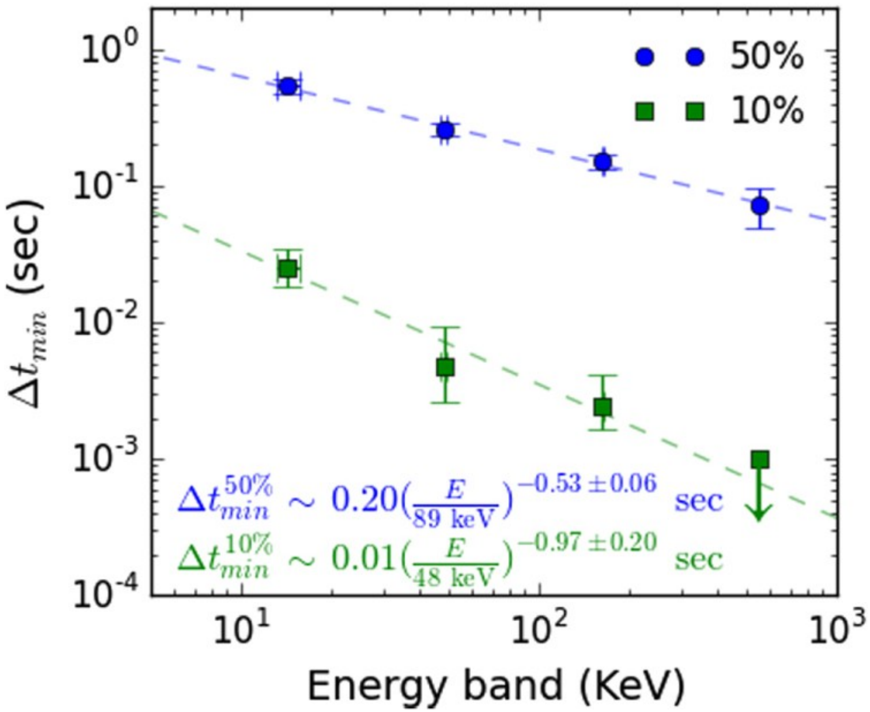
University of Ferrara

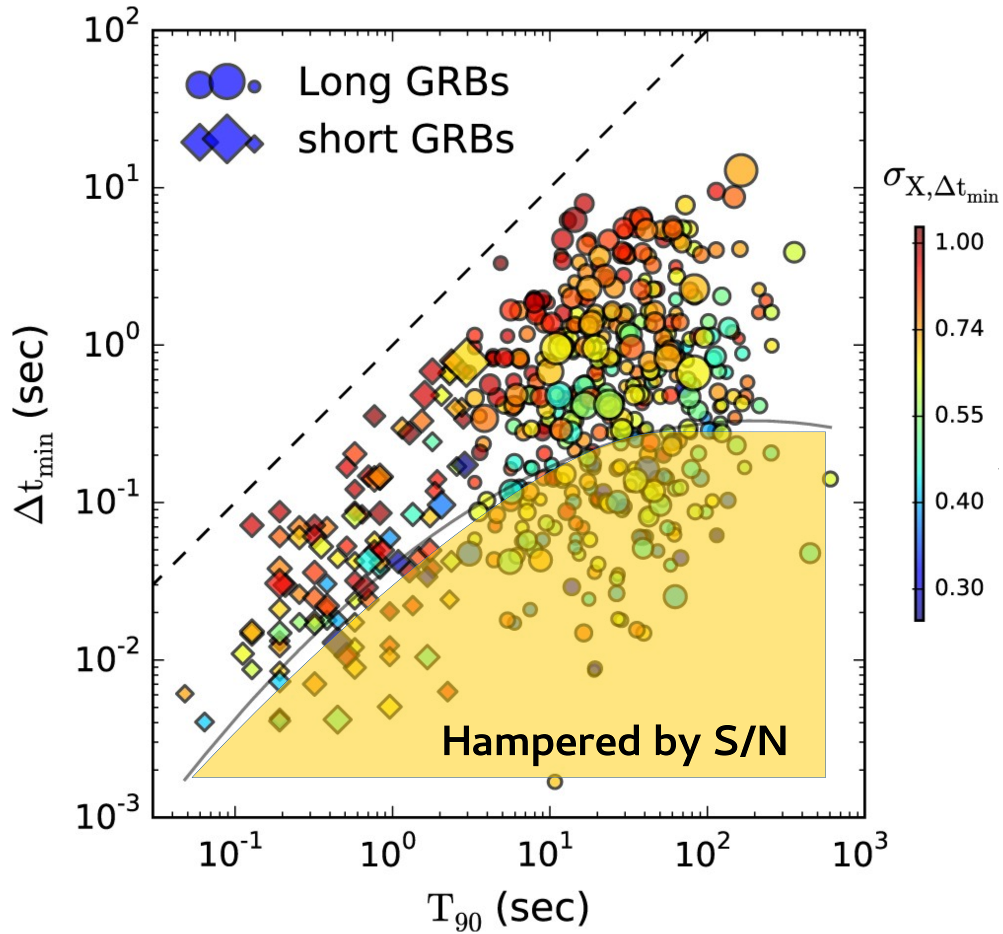
Brightest and most impulsive GRBs: only ~10% of them have < 4 ms (obs frame)
Median values (observer frame): 134 ms (long) vs. 18 ms (short)
Median values (source frame): 45 ms (long) vs. 10 ms (short)



(Golkou+15)

Minimum variability timescales (Fermi)





(Golkou+15)

Constraints on Γ_{min} and on R_{min} from Δt_{min}

University of Ferrara

$$\Gamma > \Gamma_{\rm min} = \left[\sigma_T \left(\frac{d_L(z)}{c\Delta t}\right)^2 E_c f(E_c) F(\beta)\right]^{\frac{1}{2(1-\beta)}} (1+z)^{\frac{\beta+1}{1-\beta}} \left(\frac{E_0 E_c}{m_e^2 c^4}\right)^{\frac{\beta+1}{2(\beta-1)}} .$$

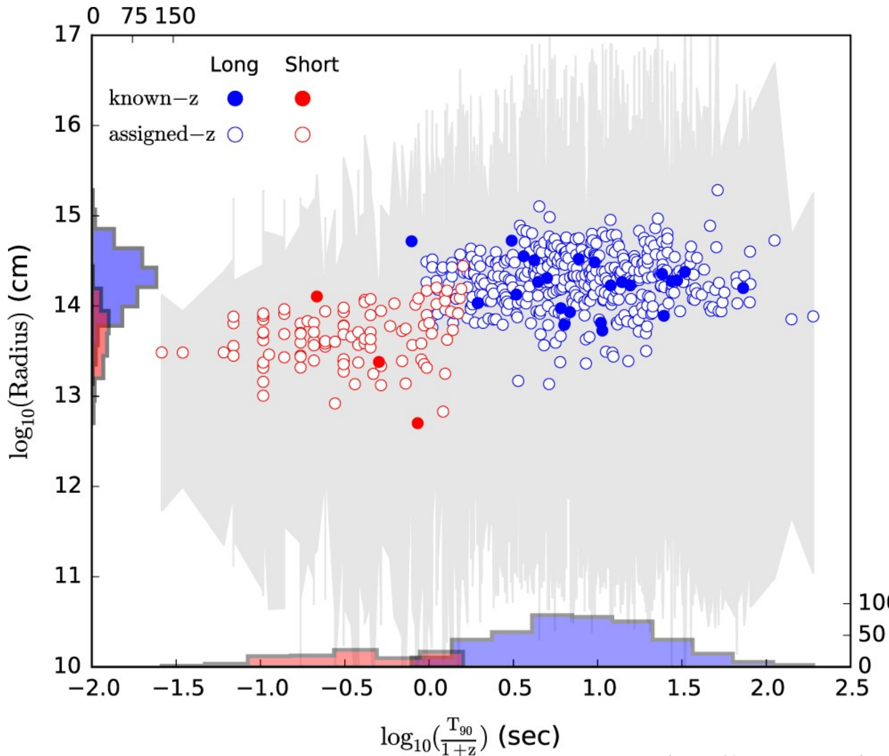
(Abdo+09; Lithwick & Sari01)

Constraint set by the need to suppress pair production up to the hardest photons observed:

$$\tau_{\gamma\gamma}(E_{max}) < 1$$

$$\tau_{\gamma\gamma}(E_0) = \sigma_{\rm T} \left(\frac{d_L(z)}{c\Delta t}\right)^2 E_c f(E_c)(1+z)^{-2(\beta+1)} \Gamma^{2(\beta-1)} \left(\frac{E_0 E_c}{m_e^2 c^4}\right)^{-\beta-1} F(\beta).$$

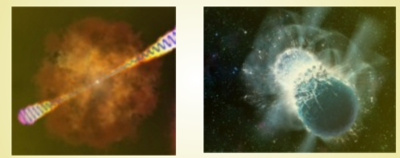
$$R_{min} = \frac{2c\,\Gamma_{min}^2 \Delta t_{min}}{1+z}$$



(Golkou+15)

University of Ferrara

Progenitors



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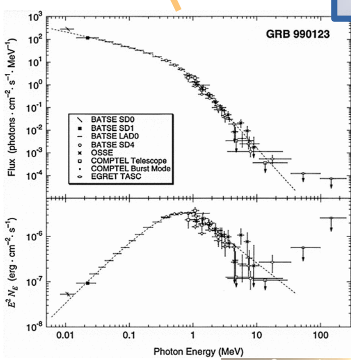

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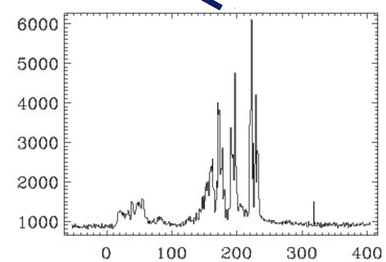
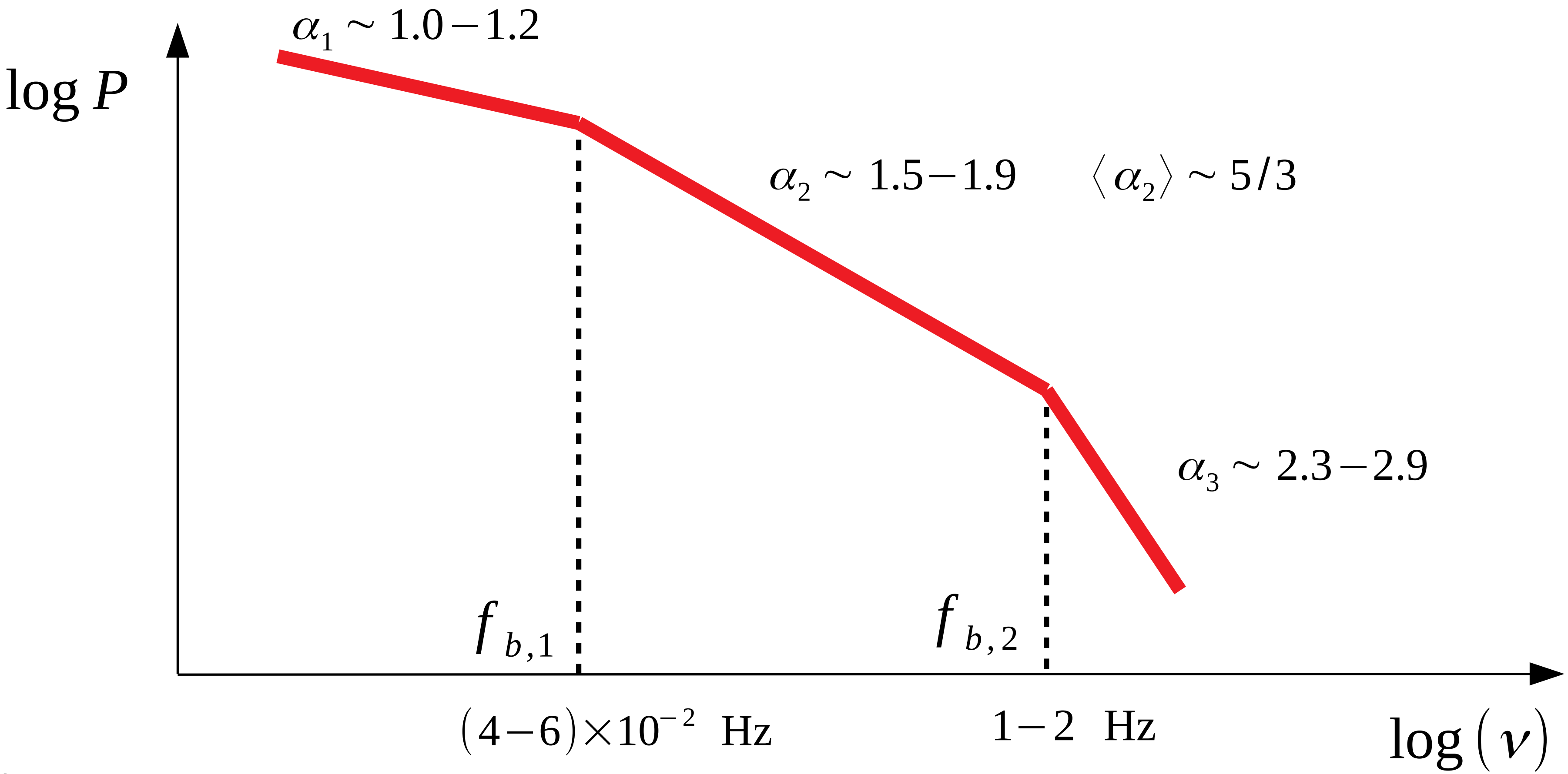


Time profiles

Average power density spectra



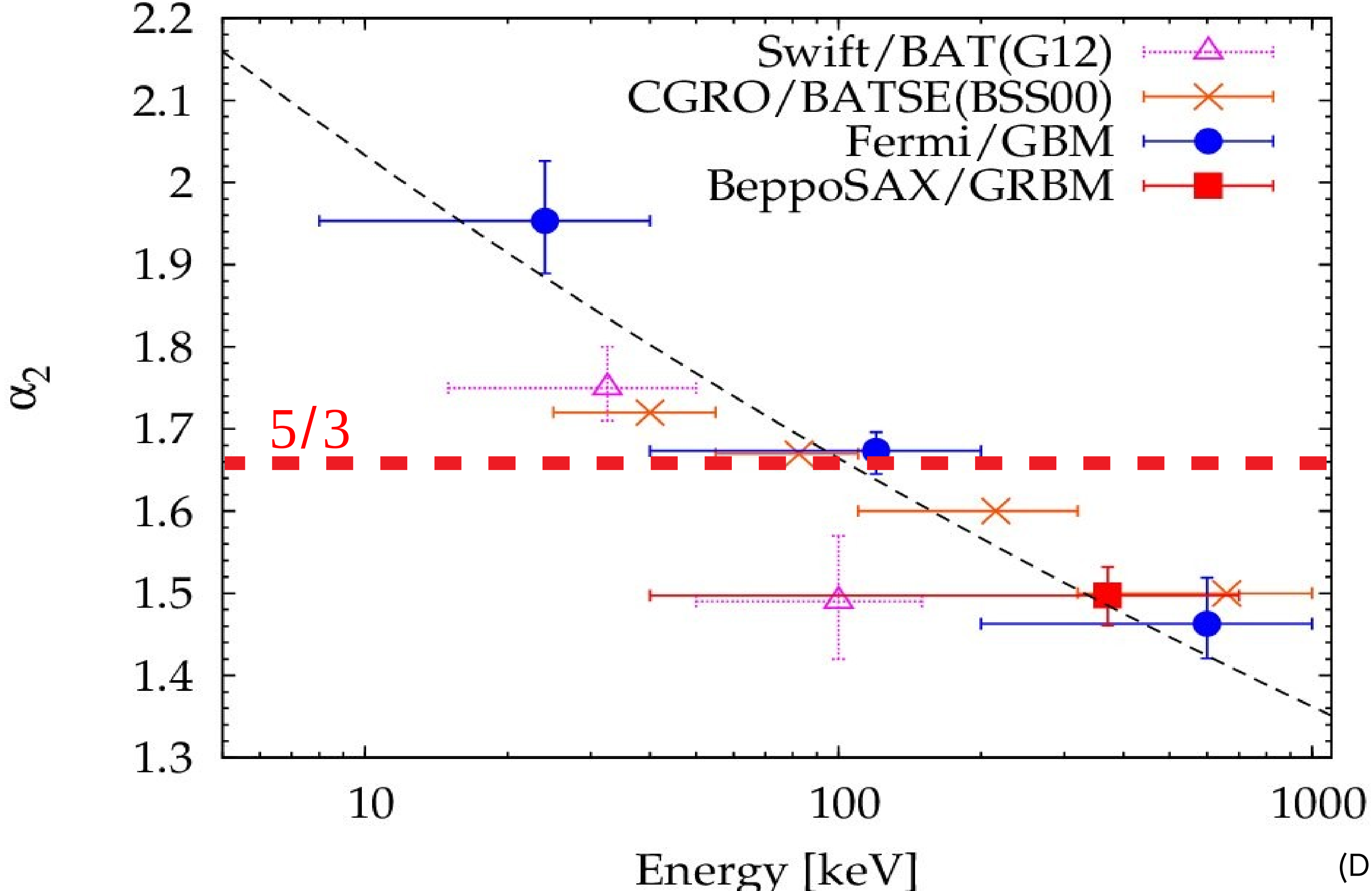
(Dichiara+13; Beloborodov98,00; CG+12)

$$\tau_1 = \frac{1}{2\pi f_{b,1}} \sim \text{few s}$$

$$\tau_2 = \frac{1}{2\pi f_{b,2}} \sim 0.1-0.2 \text{ s}$$

PDS power-law index vs. Energy

University of Ferrara



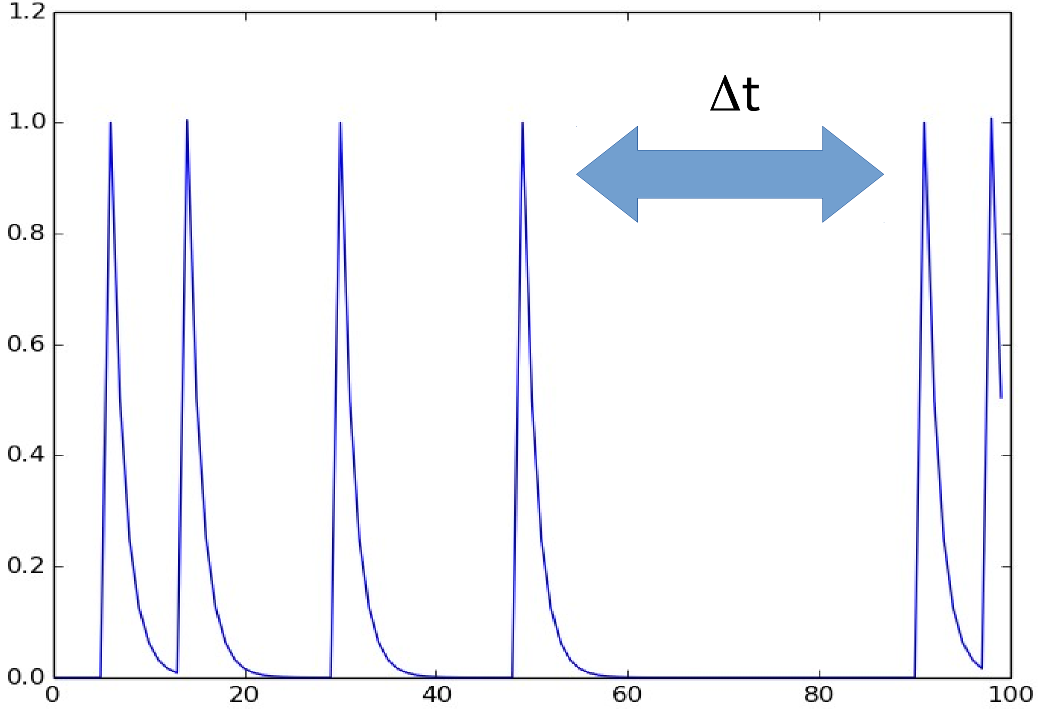
(Dichiara+13)

Inverse problem: what yields $\alpha = 5/3 - 2$?

- Fully developed turbulence Kolmogorov velocity spectrum
- Relativistic outflow of a jet making its way out through stellar envelope
- MHD turbulence (ICMART): $5/3 < \alpha < 2$
- Pair-annihilation dominated neutrino cooling triggered by MRI in accretion disc
- Many other processes

→ PDS with $5/3 < \alpha < 2$

A simple (constant) Poisson process

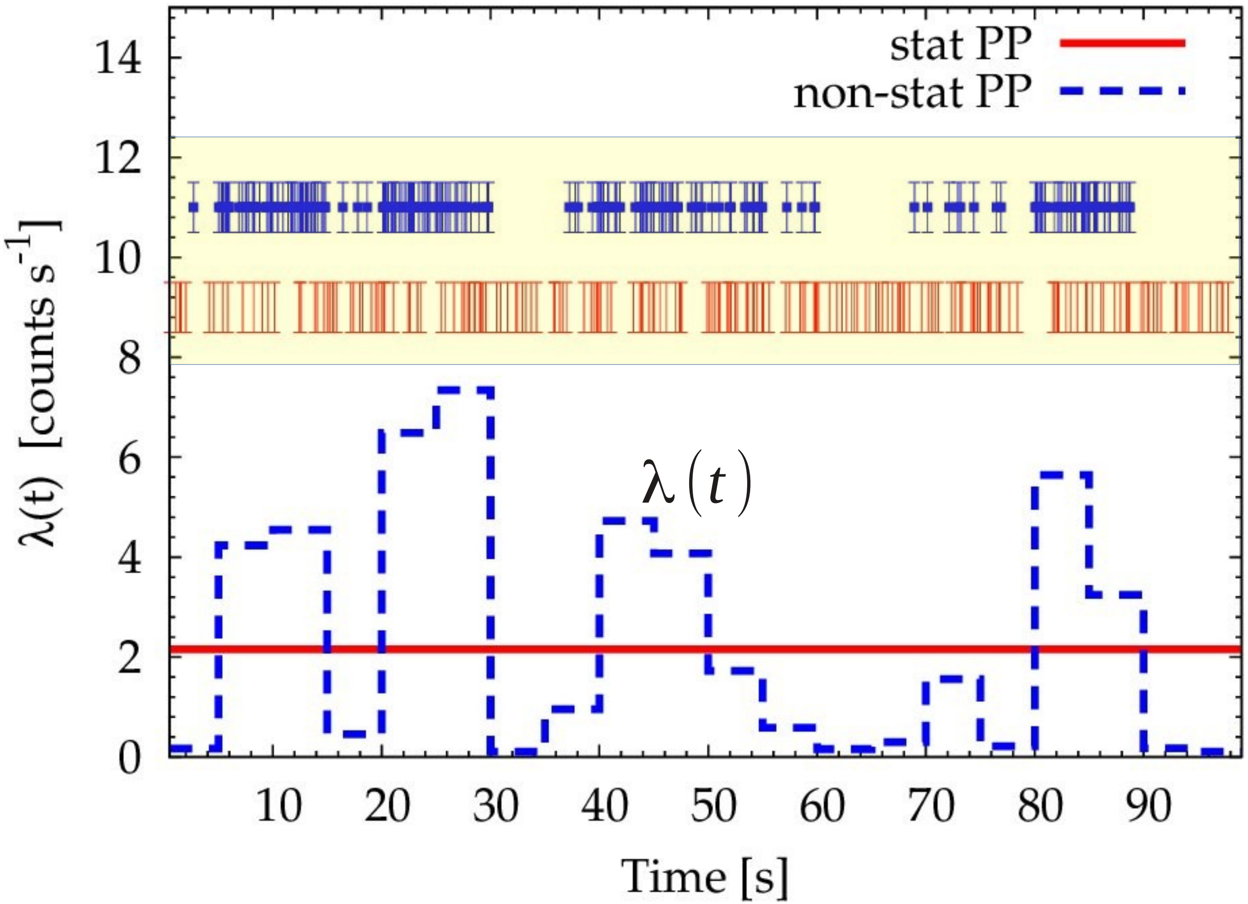


Memory-less sequence of independent shots with same probability of occurring per unit time:

$$P(\Delta t) = \frac{1}{\tau} e^{-t/\tau} = \lambda e^{-\lambda t}$$

$$\langle \Delta t \rangle = \tau = 1/\lambda$$

Time-varying Poisson process: λ=λ(t)



- At a given time t, events are generated according to a Poisson process with rate λ = λ(t) and, as such, are statistically independent
- The expected rate λ is itself a function of time, which can vary either randomly or deterministically as time passes.

(CG+15)

GRBs as time-varying Poisson process

University of Ferrara

λ = rate of pulses

Probability density distrib:

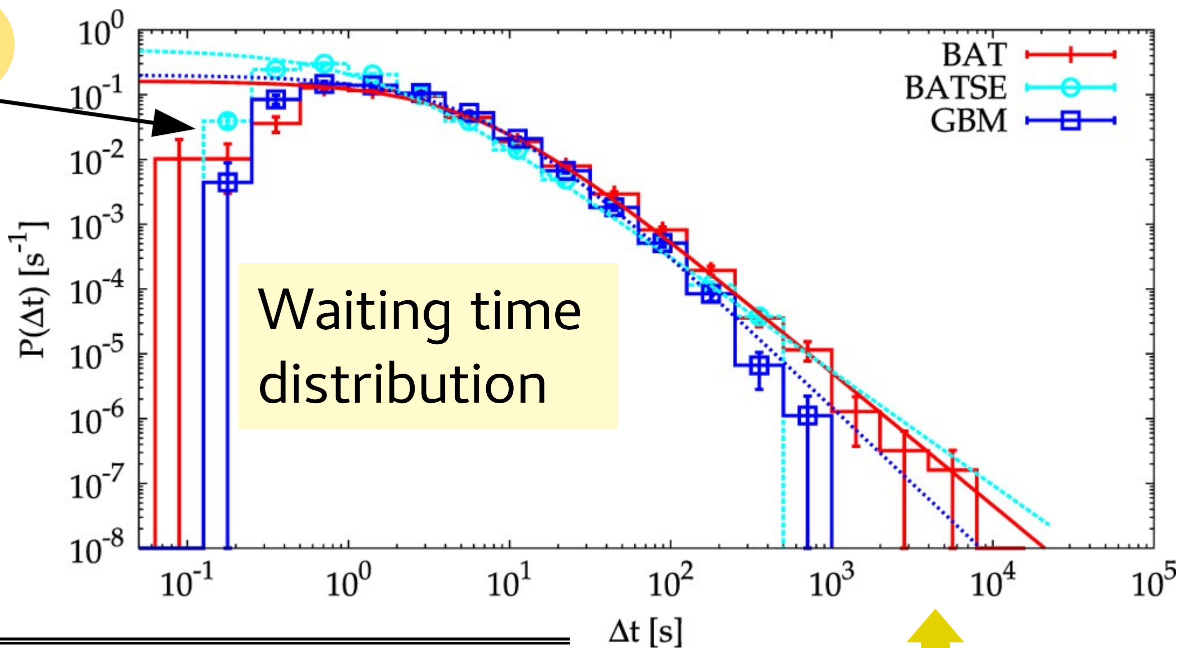
$$f(\lambda) = A\,\lambda^{-\alpha}\,\exp(-\beta\lambda)$$

(adopted for solar X-ray flares and solar energetic particle events; Li+14)

Waiting time distribution:

$$P(\Delta t) = \frac{(2-\alpha)\,\beta^{2-\alpha}}{(\beta+\Delta t)^{3-\alpha}}$$

Starving for S/N



Waiting time distribution

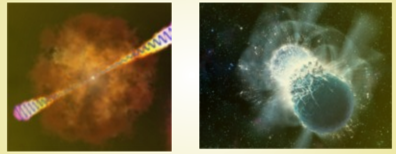
Sample	Size	α	β (s)	PL Index ($= 3-\alpha$)	CL (%)
BAT	1582	$0.94^{+0.09}_{-0.10}$	$6.53^{+1.22}_{-0.98}$	$2.06^{+0.10}_{-0.09}$	26.4
BATSE	6560	1.24 ± 0.04	$1.53^{+0.19}_{-0.16}$	1.76 ± 0.04	3.0
BATSE12	5156	1.19 ± 0.05	$2.72^{+0.33}_{-0.29}$	1.81 ± 0.05	7.5
BATSE34	4912	1.18 ± 0.05	$1.23^{+0.18}_{-0.16}$	1.82 ± 0.05	76.6
GBM	1839	$0.64^{+0.16}_{-0.17}$	$6.76^{+1.44}_{-1.14}$	$2.36^{+0.17}_{-0.16}$	36.3
BATtrunc	1445	$0.78^{+0.15}_{-0.16}$	$6.99^{+1.63}_{-1.28}$	$2.22^{+0.16}_{-0.15}$	5.2
BAT-X	854	$1.34^{+0.06}_{-0.07}$	$6.33^{+1.54}_{-1.20}$	$1.66^{+0.07}_{-0.06}$	5.4
BAT-Xz	359	$1.45^{+0.10}_{-0.11}$	$1.26^{+0.72}_{-0.42}$	$1.55^{+0.11}_{-0.10}$	18.5

GRB gamma-ray pulses and early X-ray flares together! Common dynamics

(CG+15)

University of Ferrara

Progenitors



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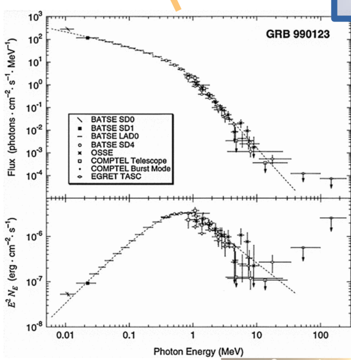

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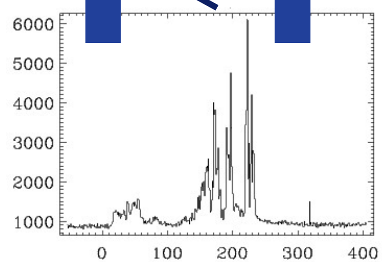

Time profiles

Thank you