Introduction to
GRB high-energy prompt emission analysis

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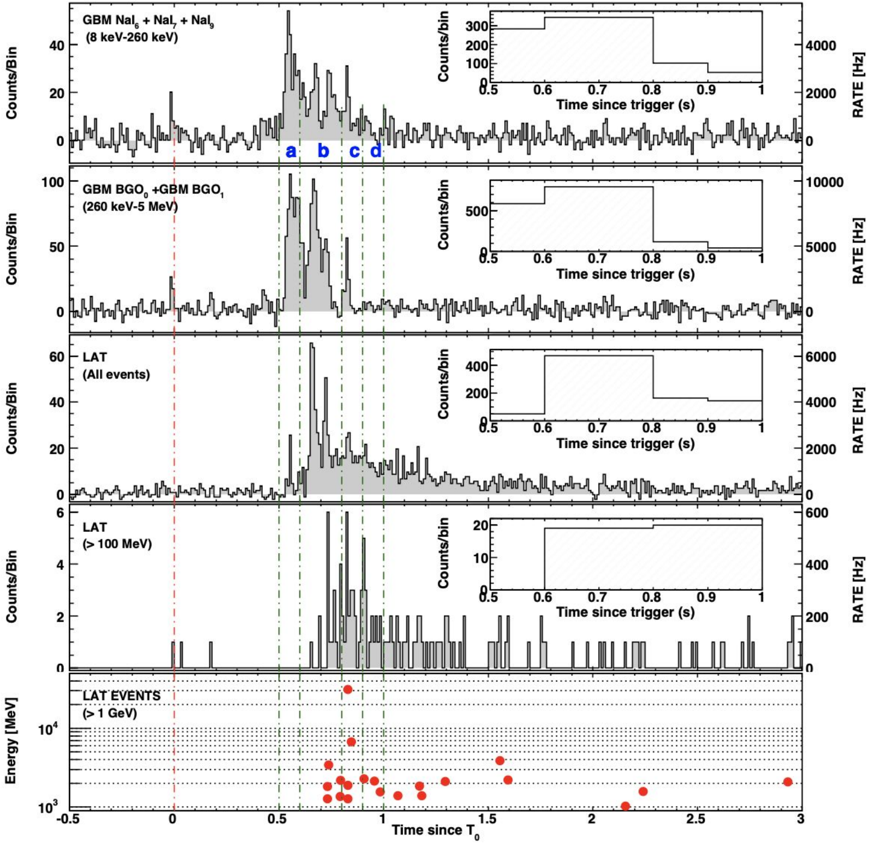
Multi-band/multi-detector light curve

- **Light curve (LC): count rate in an energy band as a function of time**
  - Usually at least one for the total energy band of each detector
  - Display also the light curves for pre-defined sub-energy bands (e.g. for ECLAIRs: 4-20 keV, 20-50 keV, 50-80 keV, 80-120 keV)
  - Time binning appropriate to the characteristics of the GRB (total duration, temporal variability, ..)

- **Preliminary considerations from the light curve**
  - Define the main emission episodes, pulses
  - Presence of a precursor?
  - Help define time intervals relevant for the spectral analysis



Light curve of GRB 090510 prompt emission in different energy bands as observed by Fermi/GBM and LAT. The vertical lines mark the trigger (red) on a precursor, and the time intervals for the spectral analysis (green)

Ackermann et al. 2010, ApJ 716, 1178

Background fit

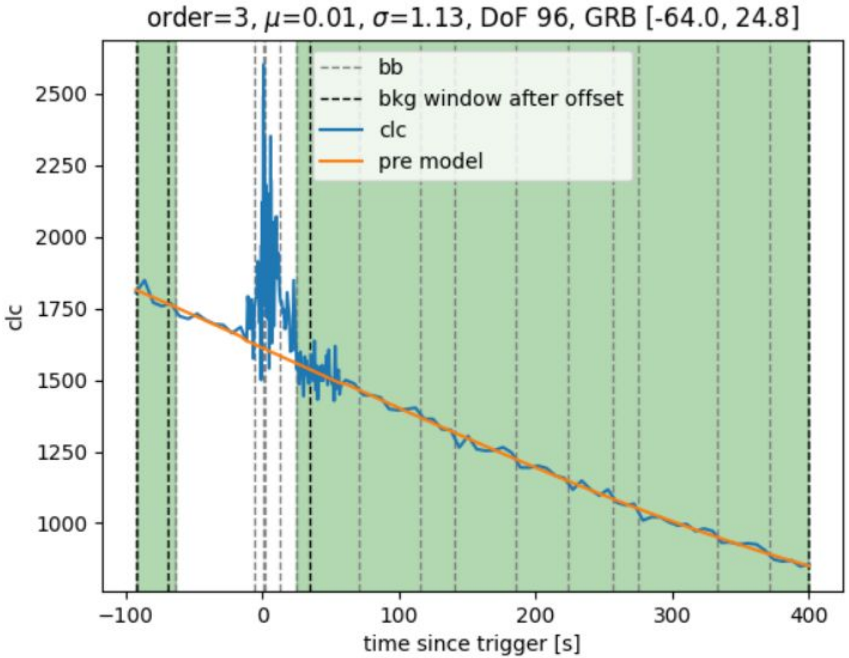
- **In case the bkg can not be removed by image deconvolution (e.g. with ECLAIRs L1 data)**
- **Define the 2 bkg regions (pre/post burst)**
    - Manually or automatically (Bayesian Blocks + search for best regions)
- **Bkg models: polynomial pol(t) (model T), or pol(Θ_{Earth}) (model E)**
    - Physical (CXB/reflexion/albedo) and more accurate model (P) after commissioning

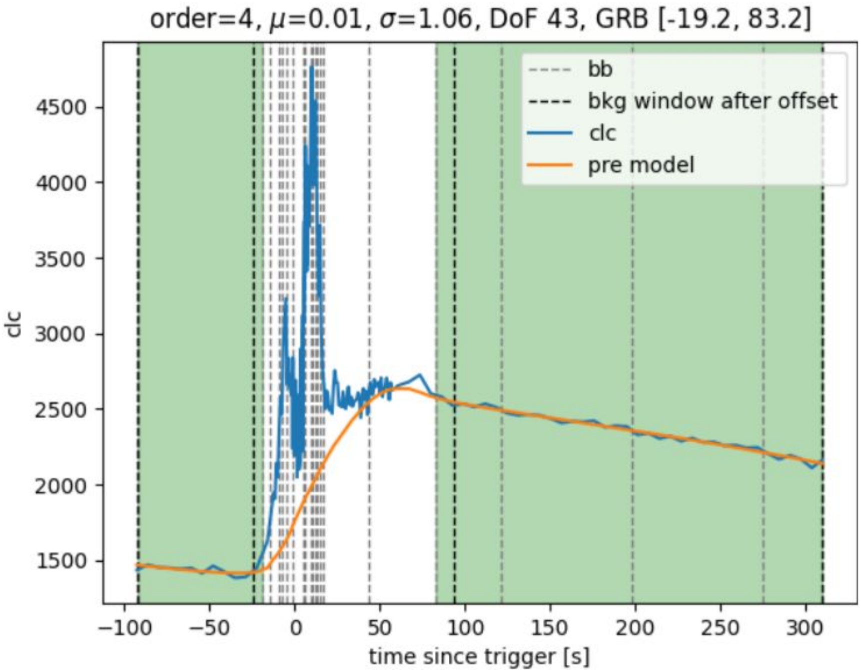
A. Maiolo's PhD thesis (2023)

ECLAIRs GRB (simulation without slew)

From J. Wang (IAP)

ECLAIRs GRB (simulation with slew)

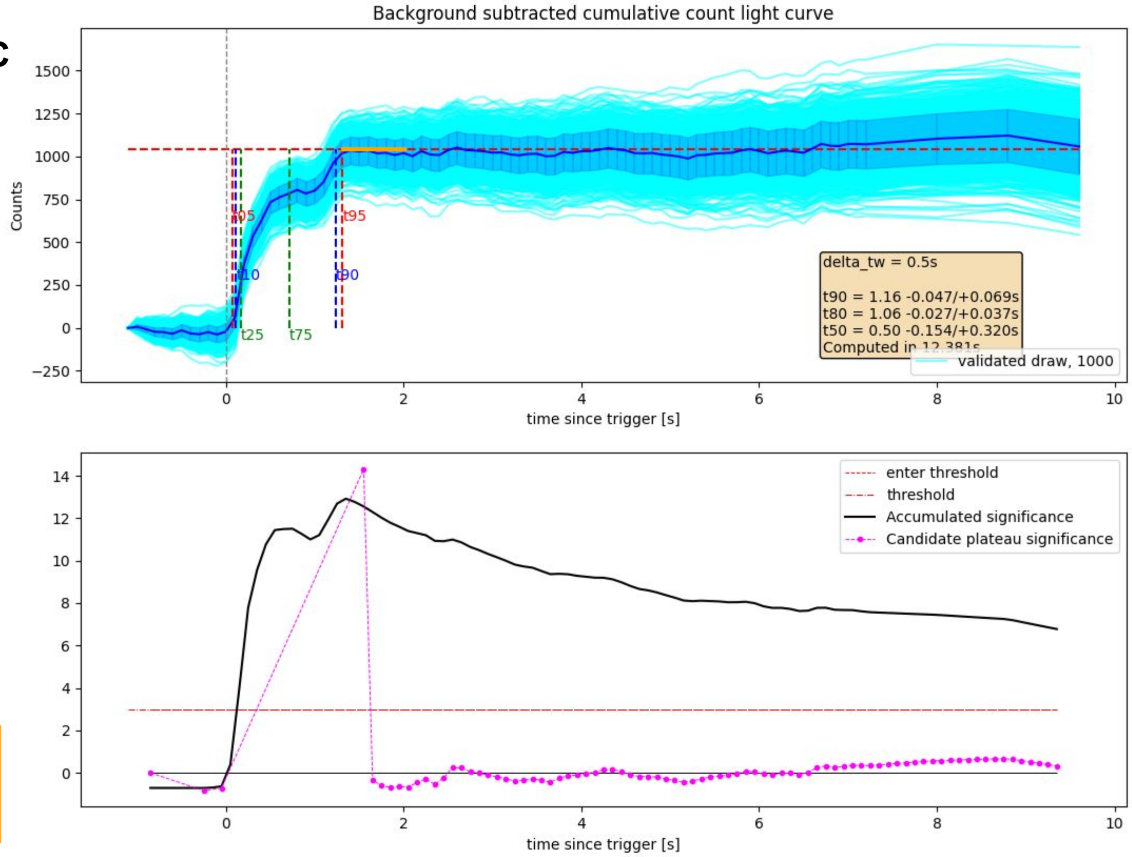

order=3, μ=0.01, σ=1.13, DoF 96, GRB [-64.0, 24.8]


order=4, μ=0.01, σ=1.06, DoF 43, GRB [-19.2, 83.2]

Observed durations (T90 etc)

- **Make bkg-subtracted cumulative count LC**
- **Find plateaux → 100% accumulation level**
- **Compute duration: T90 = t95 - t05**
  - From 5% to 95% accumulation times
  - Also T80 & T50 durations
- **Resampling → final values & errors**
- **Simple and robust**
  - Used in Fermi/LAT first GRB catalog **Ackermann+2013**
  - More sophisticated methods exist **Koshut+1996, Paciesas+2012**

- **T90: lower limit on the GRB duration**
  - Depends on SNR (i.e. detector and observing condition)

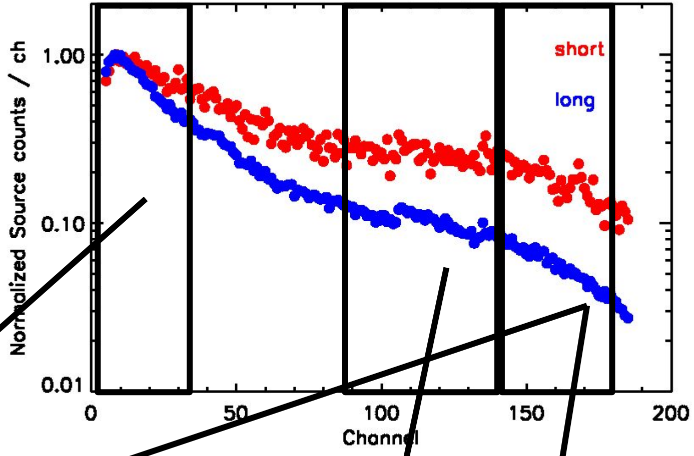


ECLAIRs simulated GRB (sb24050303) analyzed by the ECLGRM-VHF pipeline

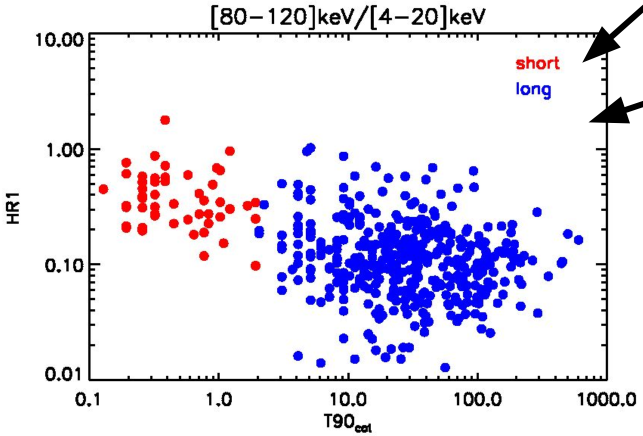
Hardness Ratio(s)

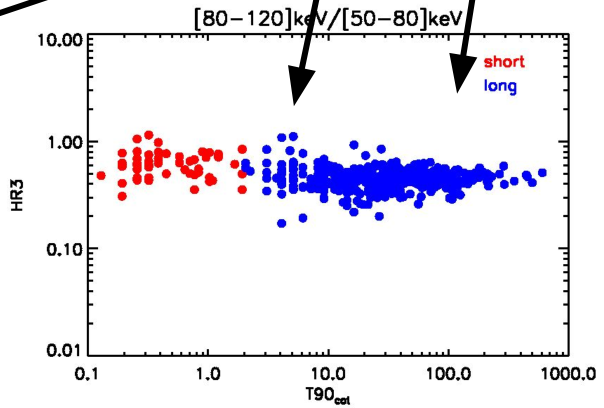
- **HR: ratio between the total number of GRB counts in two energy bands (usually high/low)**
  - Indicator of the spectral behaviour of a GRB
  - Discriminate among different classes of GRBs (short, long, X-ray rich, …)
- **Simulate HR for ECLAIRs and GRM**
  - Catalog of Fermi/GBM (Grueber et al.): cutoff power-law model (50 short, 396 long) → ECLAIRs and GRM
  - Time-integrated spectra over T100 simulated with Xspec with the latest responses and average bkg
  - HR calculated integrating simulated spectra

ECLAIRs normalised mean count spectra for simulated long and short GRBs from Fermi/GBM catalog



HR vs. T90 for the Fermi/GBM catalog simulated with ECLAIRs





Spectral components of GRB prompt emission

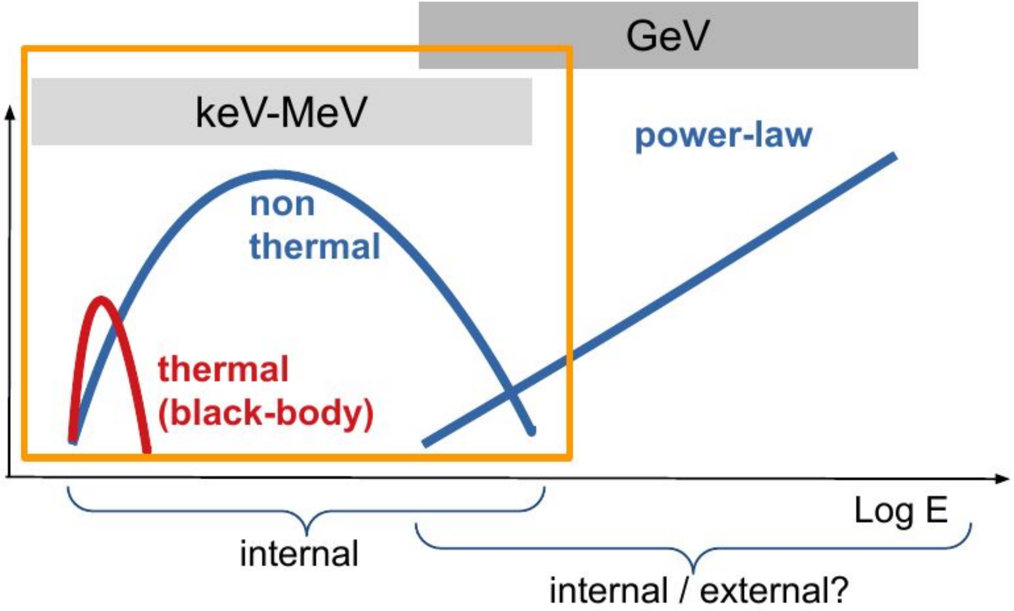
- **<u>Photon spectrum f(E) [ph/cm²/s/keV]</u>**
  → SED = E² x f(E) [erg/cm²/s]

- **Main component: non thermal**
  → synchrotron? (after energy dissipation by internal shocks or magnetic reconnection)

- **Additional components**
  - <100 keV: quasi-thermal
    → photospheric emission?
  - GeV: power law
    → prompt SSC or early afterglow?

- **Other possible features**
  - <50 keV: flux excess, spectral break (e.g. cooling break)
  - MeV-GeV: spectral cutoff (end of particle distribution or γγ opacity), line (BOAT)

Typical SED of GRB prompt keV-GeV emission



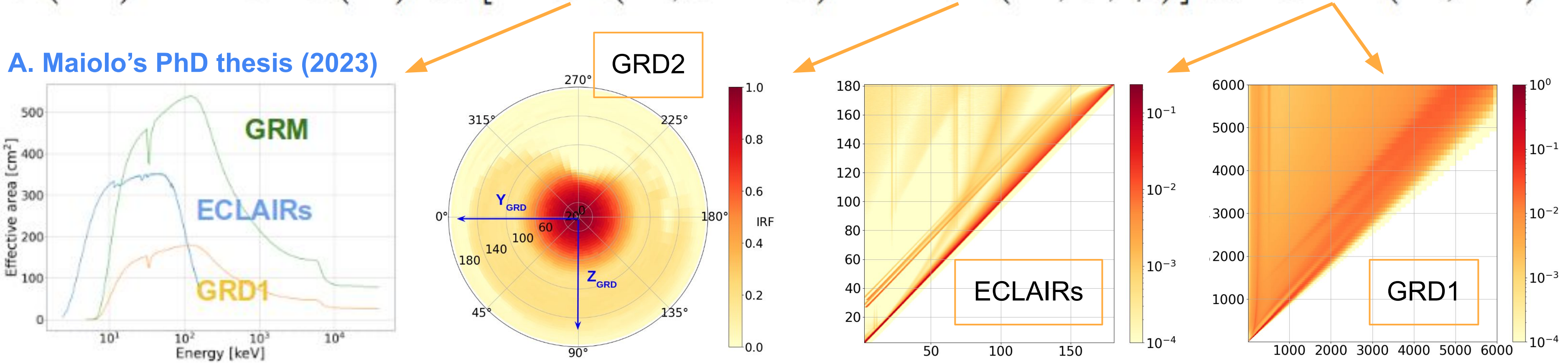
- **Physical interpretation needs time-resolved (or pulse-resolved) spectral analysis to identify the emission components and their temporal evolution**

Spectral analysis : methodology

- **Observed counts spectrum [counts/s/keV] – here for a Band spectrum f(E)**

$$r(E') = \mathrm{Band}(E) \circledast [\mathrm{ARF}(E, \theta = 0) \times \mathrm{IRF}(E, \theta, \phi)] \circledast \mathrm{RMF}(E, E')$$

A. Maiolo’s PhD thesis (2023)



- **Forward-folding spectral analysis: assume a spectral model f(E) and fold it with the detector response**
  - Because energy dispersion can not be easily inverted / corrected (especially for GRM)
- **Maximize the likelihood L(D|M) to get the data and background counts given the spectral model M = f(E)**
  - Hypothesis testing tool: it can only tell you about what you put into the model
- **Standard approach**
  - Model fitting: Maximum Likelihood Estimation (MLE) of the spectral model parameters
  - Model comparison: Likelihood Ratio Tests (LRT) – in the frequentist approach…

Spectral models f(E)

Phenomenological models (mostly for basic characterization)

- [2 params] Power Law (PL)
- [3 params] Cutoff Power Law (CPL / CUTPL / COMPtonized)
- [4 params] Broken Power Law (BPL)
- [4 params] **Band : α, β, Ep, norm**
- [5 params] Smoothly Broken Power Law (SBPL)
- …

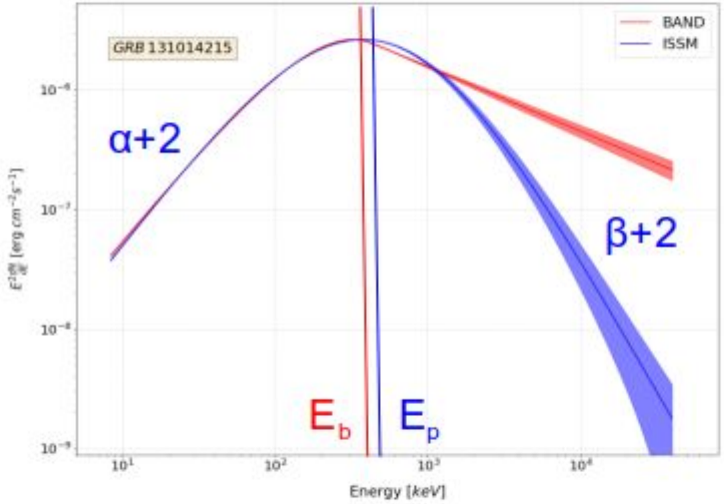
See L. Scotton's PhD thesis (2023) for f(E) expressions

Physical models (for interpretation)

- [2 params] Black-Body (BB)
- [4 params] **ISSM : α, β, Ep, norm**
  - Proxy for GRB **Internal Shock Synchrotron Model**
  - Continuously curved unlike Band + better fits
- f(E) from analytical and/or numerical computations
  - Synchrotron from an e⁻ population (simple model)
  - GRB synchrotron with outflow dynamics (more realistic)
- …

Yassine et al. 2020, A&A 640, 91

SED of Fermi/GBM GRB131014A
from Band & ISSM spectral fits



$$f_{\mathrm{Band}}(E) = A \times \begin{cases} \left(\frac{E}{E_{\mathrm{piv}}}\right)^{\alpha} \exp\left[-\frac{E(2+\alpha)}{E_p}\right] & \text{if } E \leqslant E_b = E_p \frac{\alpha-\beta}{2+\alpha} \\ \left(\frac{E}{E_{\mathrm{piv}}}\right)^{\beta} \exp(\beta-\alpha)\left[\frac{E_p(\alpha-\beta)}{E_{\mathrm{piv}}(2+\alpha)}\right]^{\alpha-\beta} & \text{otherwise} \end{cases},$$

$$f_{\mathrm{ISSM}}(E) = \frac{A}{\left[1-\frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}} \times \left(\frac{E}{E_r}\right)^{\alpha}\left[\frac{E}{E_r}-\frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha},$$

Both Band & ISSM → CPL when β → – inf

Spectral analysis : procedure

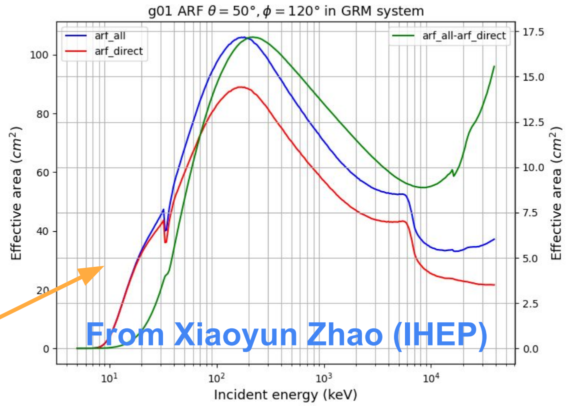
- **Define time intervals (emission episodes, pulses, etc) to be analyzed**

- **Make counts spectra (from L1 event data)**
    - Energy channels: pseudo-logarithmic, according to energy resolution
    - Counting technique (GRM, possibly ECLAIRs): for each energy channel, fit bkg in 2 LC regions and extrapolate to time interval
    - Imaging technique (ECLAIRs): for each energy channel, fit the shadowgram to extract the (localized) GRB counts and variance

- **Make detector response matrices (DRM = Aeff x RMF @ Θ_{GRB})**
    - GRM: account for GRB photons scattered by Earth atmosphere
        - If not included, can mimic fake spectral component

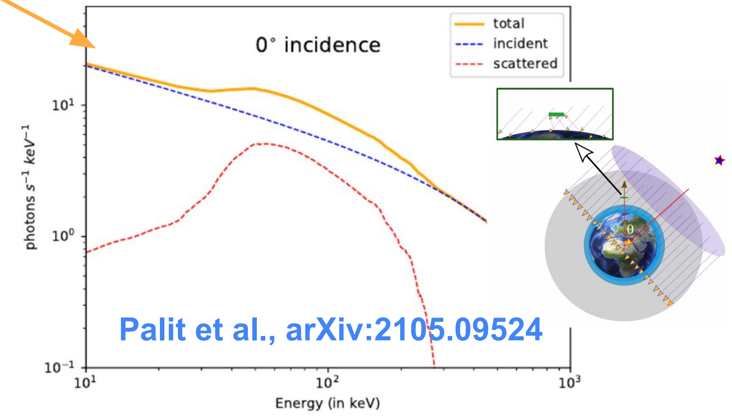
- **Fit spectral model – e.g. with (py)XSPEC**
    - Load counts spectra and DRM of each detector
    - Select energy channels (e.g. ignored near GRM Iodide K-edge)
    - Choose the spectral model f(E)
    - Choose the proper fit statistics among variants of -2*log[L(D|M)]
        - *cstat*, *pgstat*, *chi* (see Statistics in XSPEC)
    - MLE of f(E) parameters (and their covariance matrix)
    - Assess fit quality from residuals & goodness of fit (e.g. chi² prob.)
    - Sample best spectral parameters to get SED contour, fluxes, etc

GRD effective area with/without scattering



From Xiaoyun Zhao (IHEP)

Simulated AstroSat-CZTI Band count spectra with/without atmospheric scattering



Palit et al., arXiv:2105.09524

Spectral fit examples : ECLAIRs + GRM

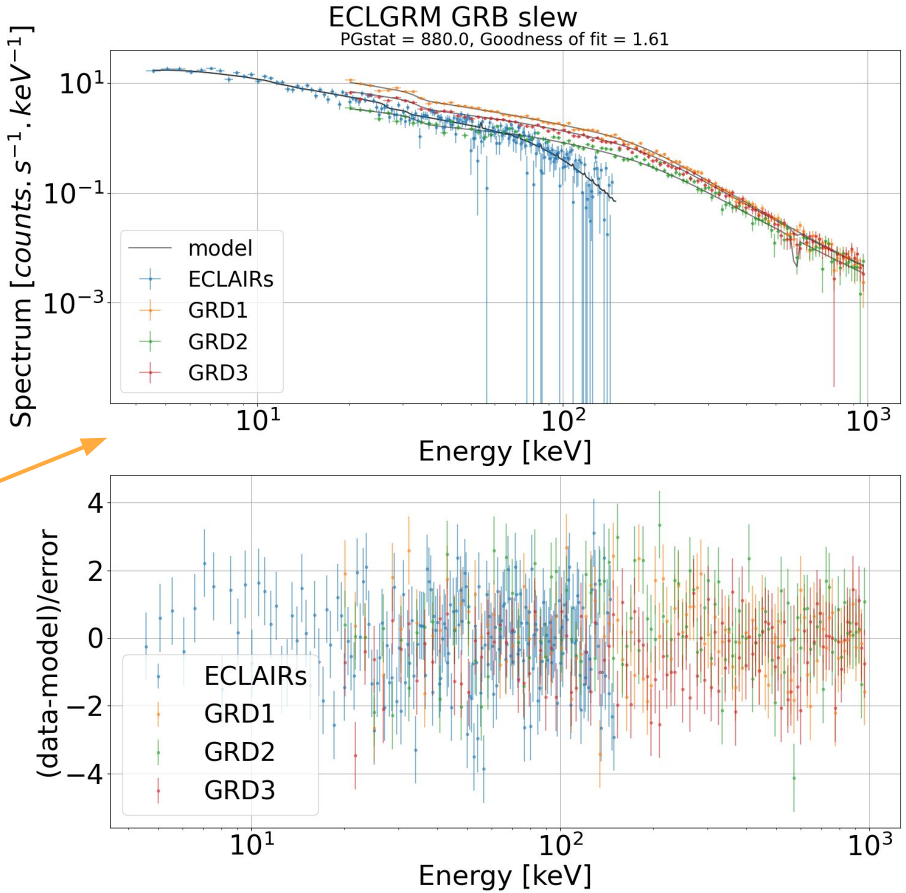
- **Very fluent GRB (10^{-4} erg/cm2)**
  - α = −1.19, β = −2.07, Epeak = 467 keV
- **Bkg model E (“simple”)**
  - α & Ep well measured (within ~2σ)
  - but β and flux badly constrained
- **Bkg model P (“physique”) → excellent results**

A. Maiolo’s PhD thesis (2023)

Sursaut gamma très fluent

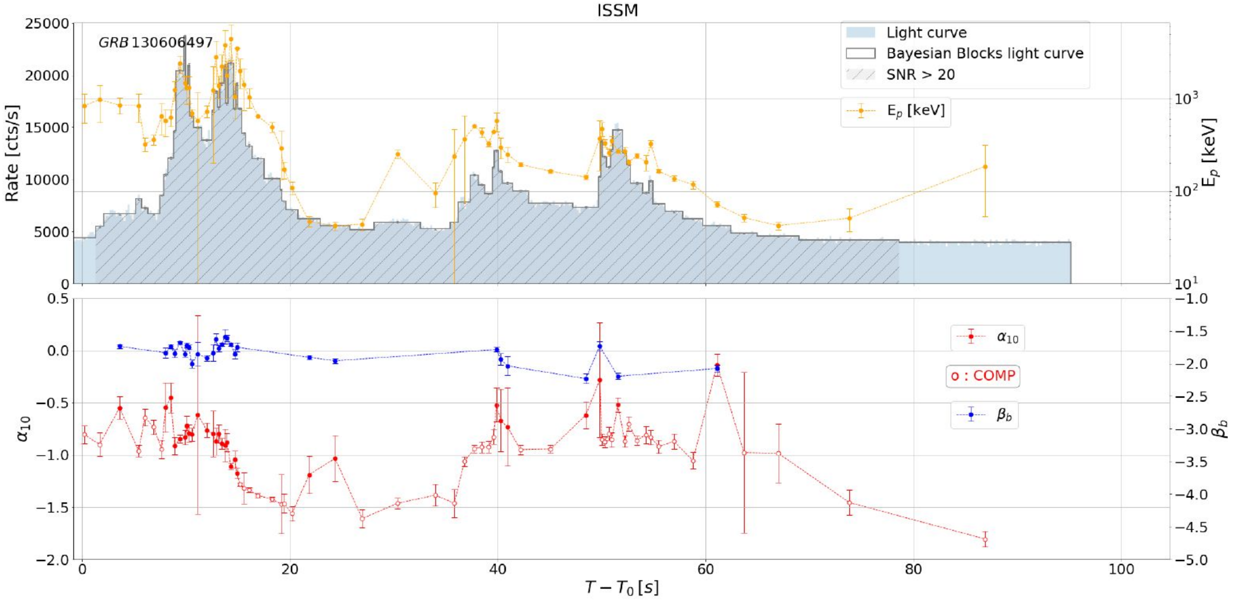
Instrument	ECLAIRs		GRM		ECLAIRs + GRM	
Modèle	simple	physique	simple	physique	simple	physique
PGstat réduit	2.0	1.9	1.7	1.4	1.9	1.6
K_{100} (10^{-2}.cm^{-2}.s^{-1}.keV^{-1})	0.85 ± 0.02 (-0.2, 7.5σ)	0.85 ± 0.02 (-0.2, 7.5σ)	1.01 ± 0.02 (0.005, 2.2σ)	1.04 ± 0.02 (0.002, 1.1σ)	1.03 ± 0.02 (0.002, 1.0σ)	1.01 ± 0.01 (-0.006, 0.4σ)
α	-1.25 ± 0.02 (0.07, 4.4σ)	-1.25 ± 0.02 (0.07, 4.4σ)	-1.11 ± 0.02 (0.07, 3.7σ)	- 1.14 ± 0.02 (0.04, 2.4σ)	-1.15 ± 0.01 (0.03, 2.2σ)	-1.17 ± 0.01 (0.01, 1.1σ)
β	-	-	-9 ± 41069 (-7, -)	-2.06 ± 0.08 (0.1, 0.1σ)	-9 ± 57789 (-7, -)	-2.1 ± 0.1 (0.03 , 0.3σ)
E_{peak} (keV)	-	-	411 ± 27 (56, 2.1σ)	433 ± 27 (-34, 1.3σ)	440 ± 28 (-27, 0.9σ)	468 ± 25 (1.74, 0.7σ)
Flux (cm^{-2}.s^{-1})	1.84 ± 0.03	1.83 ± 0.03	1.80 ± 0.90	1.84 ± 0.01	1.90 ± 0.90	1.86 ± 0.01
Flux/Flux_{reel}	0.97 ± 0.01	0.97 ± 0.02	0.97 ± 0.47	0.97 ± 0.01	0.99 ± 0.47	0.98 ± 0.01

GRB counts spectra and residuals for a joint ECLAIRs & GRM spectral fit

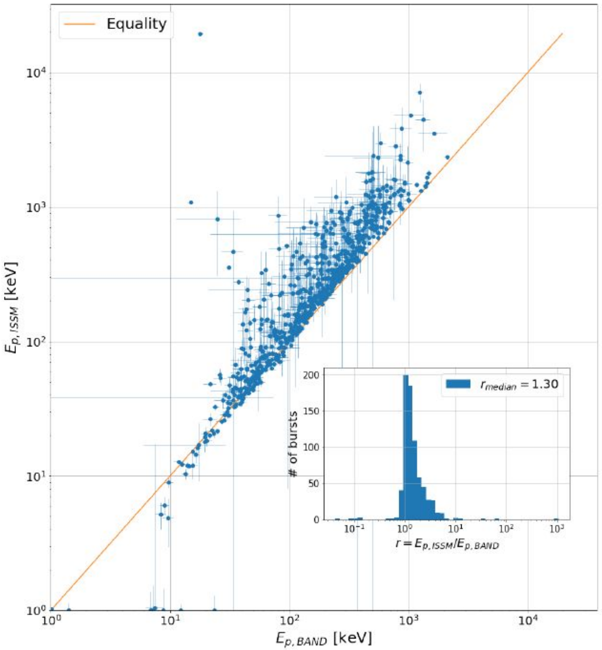


Spectral fit examples : time-resolved analysis

Fermi GRB130606B: time-resolved spectral analysis with ISSM spectral model



ISSM vs. Band peak energy Ep
from the time-resolved spectral analysis of
728 time intervals of Fermi fluent GRBs



L. Scotton's PhD thesis (2023)
Scotton et al. 2024, in preparation

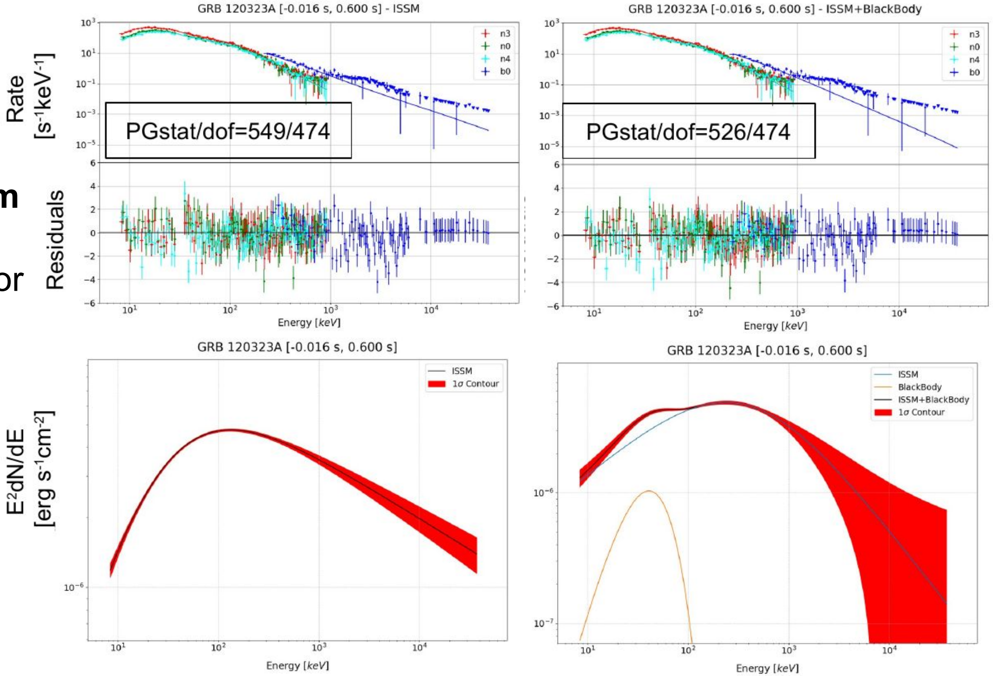
Comparing spectral models (1/2)

- **Increase gradually the model complexity**
  - E.g. PL → CPL → Band or ISSM
  - Add new components if suggested by residuals

- **Choose between 2 models M0 and M1 using the LRT**
  - Test Statistic: TS = -2*log[L(D|M0) / L(D|M1)]
  - Nested models: TS ~ chi²(dof=n) for n additional parameters between M0 and M1

- **Exercise your own judgement (the counts spectrum tells the spectroscopist what to believe or not)**
  - E.g., a large residual near an edge in the detector energy domain is likely due to poorly calculated response

Fermi short GRB120323A: fits, residuals and SED with ISSM (left) and ISSM + BB (right):
BB significance of 4.4σ (5.9σ with Band)



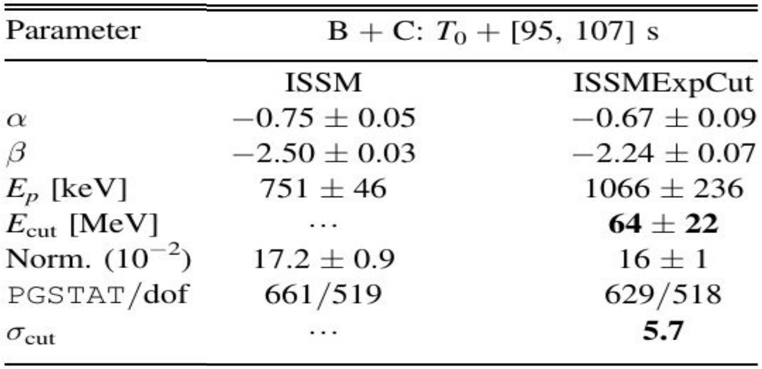
GRB 120323A	Band	Band+BB	ISSM	ISSM+BB
PG-stat/dof	571/474	532/472	549/474	526/472
$TS_{BB}(\sigma)$	-	39 (5.9)	-	23 (4.4)
α	-1.04 ± 0.06	-1.45 ± 0.03	-0.40 ± 0.27	-1.35 ± 0.05
β	-2.06 ± 0.02	-2.64 ± 0.25	-2.27 ± 0.04	-3.00 ± 0.47
E_p (keV)	79 ± 6	269 ± 28	132 ± 7	236 ± 20
nTh norm (10^{-2})	95 ± 12	32 ± 2	1.02 ± 0.03	1.09 ± 0.03
kT (keV)	-	11 ± 1	-	10 ± 1
Th norm	-	20 ± 2	-	17 ± 2

L. Scotton's PhD thesis (2023)
Scotton et al. 2024, in preparation

Comparing spectral models (2/2)

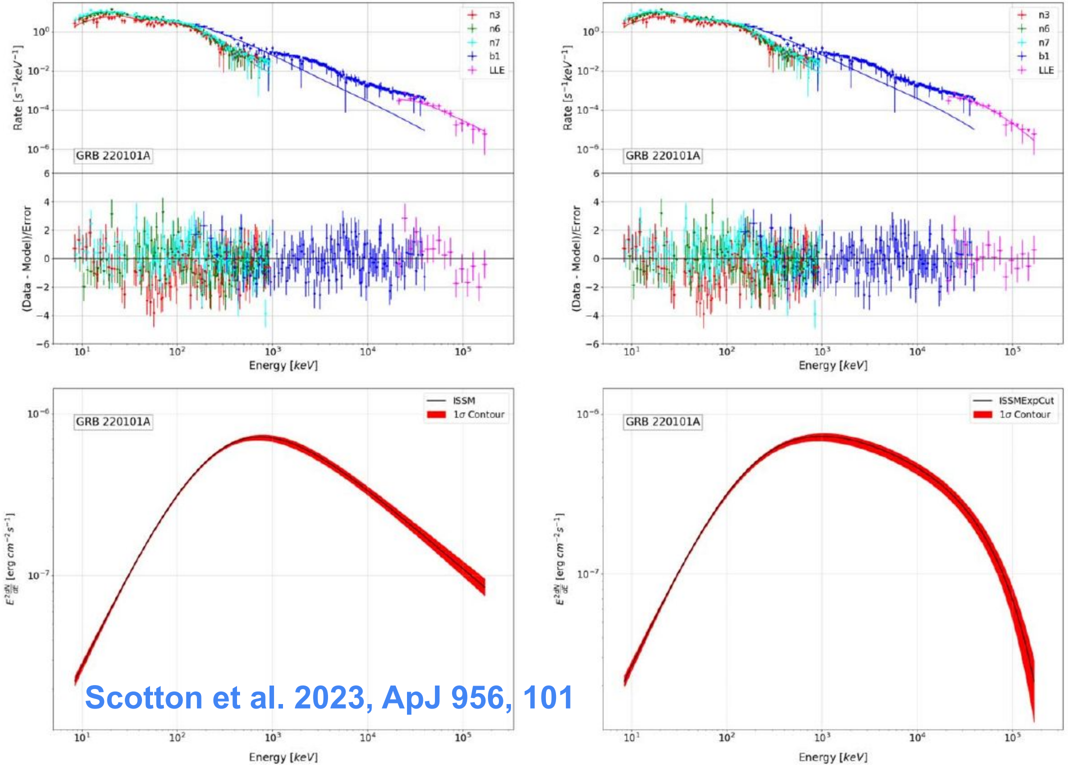
- **Models that appear very similar in data space can show different SED due to the effect of the response**
- **This is why we must pay attention to the statistical procedures we use to fit data**

- **Good practices to remember**
    - Use the proper fit statistics
    - Fit quality: show count spectra (data – unchangeable – and folded model), residuals & g.o.f.
    - SED contour: for crude comparisons only, always stating the model used



Parameter	B + C: T_0 + [95, 107] s	
	ISSM	ISSMExpCut
α	-0.75 ± 0.05	-0.67 ± 0.09
β	-2.50 ± 0.03	-2.24 ± 0.07
E_p [keV]	751 ± 46	1066 ± 236
$E_{\rm cut}$ [MeV]	···	**64 ± 22**
Norm. (10^{-2})	17.2 ± 0.9	16 ± 1
PGSTAT/dof	661/519	629/518
$\sigma_{\rm cut}$	···	**5.7**

Fermi GRB220101A high-energy spectral cutoff: fits, residuals and SED with ISSM (left) and ISSM * ExpCut (right)



Scotton et al. 2023, ApJ 956, 101

Physical quantities derived from spectral analysis

- **Once the best spectral model f(E) is chosen:**
  - Compute the photon (energy) flux p (f) in a given energy band [e_1,e_2]:

$$p_{[e_1,e_2]} = \int_{e_1}^{e_2} f(E)dE \qquad \left[\frac{1}{s\,cm^2}\right]$$

$$f_{[e_1,e_2]} = \int_{e_1}^{e_2} E\,f(E)dE \qquad \left[\frac{erg}{s\,cm^2}\right]$$

  - Compute the photon (energy) fluence by multiplying the flux by the duration of the time interval Δt:

$$P_{[e_1,e_2]} = p_{[e_1,e_2]} \times \Delta t \qquad \left[\frac{1}{cm^2}\right]; \qquad S_{[e_1,e_2]} = f_{[e_1,e_2]} \times \Delta t \qquad \left[\frac{erg}{cm^2}\right]$$

- **If the redshift z is known for the GRB:**
  - Compute the “bolometric” (usually [1,10^4] keV) isotropic energy E_{iso} and luminosity L_{iso}:

$$L_{iso} = 4\pi d_l(z)^2 \int_{1/(1+z)\,keV}^{10^4/(1+z)\,keV} E\,f(E)dE \qquad \left[\frac{erg}{s}\right]$$

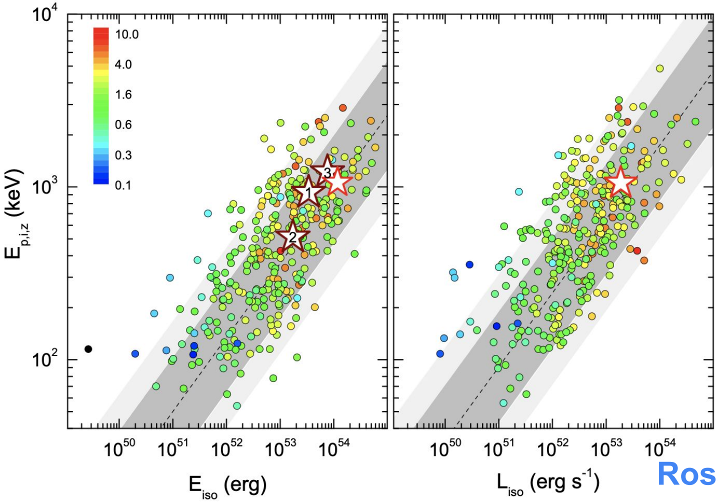
$$E_{iso} = \frac{4\pi d_l(z)^2}{(1+z)\Delta t} \int_{1/(1+z)\,keV}^{10^4/(1+z)\,keV} E\,f(E)dE \qquad [erg]$$

Amati et al. 2002, A&A 390, 81A
Bloom et al. 2001, ApJ 121, 6

Comparing the GRB properties with the GRB populations

The temporal and spectral analysis of the prompt emission provides a set of physical quantities that can be used to characterise the GRB with respect to the known populations of GRBs.

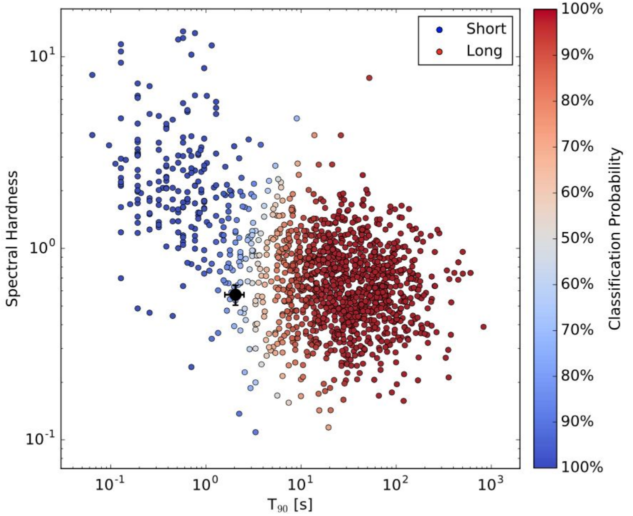
- **Short vs. Long GRBs**
    - T90 vs. hardness ratio
    - Amati (Epk-Eiso) and Yonetoku (Epk-Liso) correlations
    - **Complementary information from external facilities crucial for a correct classification**: host galaxy (type, offset), association with a supernova or a kilonova (e.g. **Rastinejad et al. 2022, Nature 612, 223; Rossi et al. 2022, ApJ 932, 1**)
    - Ultimately identify the nature of the progenitor



The rest-frame energetics of the high-z GRB 210905A (star) in the Amati (left) and Yonetoku (right) planes. The correlations for long GRBs are in grey. Color gradients represent the redshift of each GRB in the plane

Rossi et al., 2022, A&A 665, A125

T90 vs. HR for GRB 170817A (black dot) compared to the Fermi/GBM GRBs. The color gradient represents the probability of being a short or long GRB



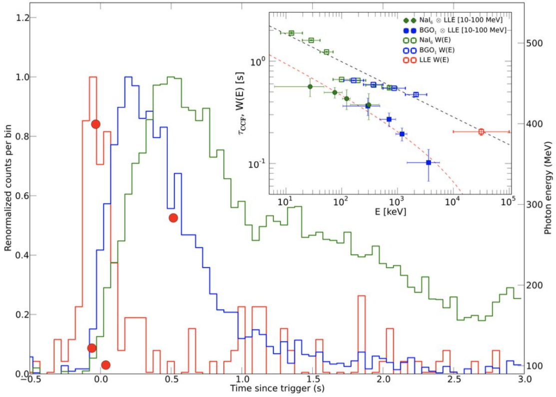
Goldstein et al. 2017, ApJL 848, L14

Light curve properties in different energy bands

In special cases of bright GRBs, a more in-depth analysis of the prompt emission can be performed by binning the light curve in sub-energy bands

- **Spectral lag τ(E): difference in arrival time of GRB pulses in different energy bands**
  - Computed using Discrete Cross-Correlation Function (DCCF) with respect to a reference band
  - Used as indicator for the GRB nature (**Norris et al. 2001**)
- **Pulse width vs. energy w(E)**
  - Low energy pulses are wider than high energy pulses: w ~ E^{-a} with a~0.4 (**Norris et al. 1996**)
- **Minimum variability timescale with significant flux variation**
  - Structure Function (SF) estimator (**Golkhou et al. 2014, 2015**)
  - Used to estimate the size of the emitting region

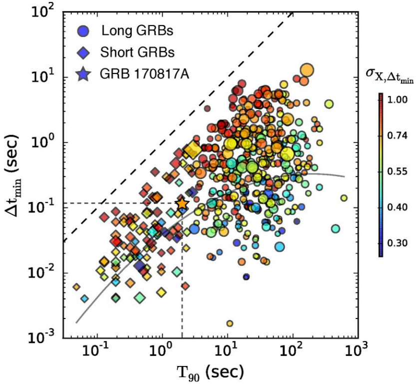
Composite normalised light curves in different energy bands of the very bright GRB 130427A from Fermi/GBM and LAT. Inset: Lag and pulse width analysis.

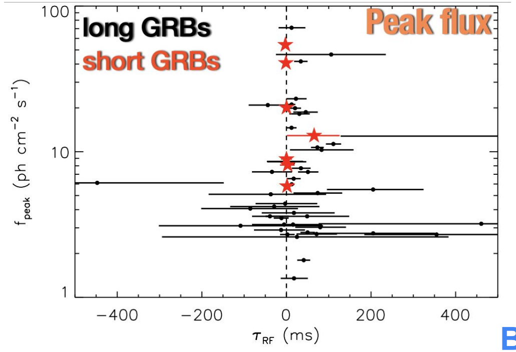


Preece et al. 2014, Science 343, 6166

Minimum variability timescale vs. T90 for GRB 170817A (star) compared to Fermi/GBM GRBs.

Goldstein et al. 2017, ApJL 848, L14





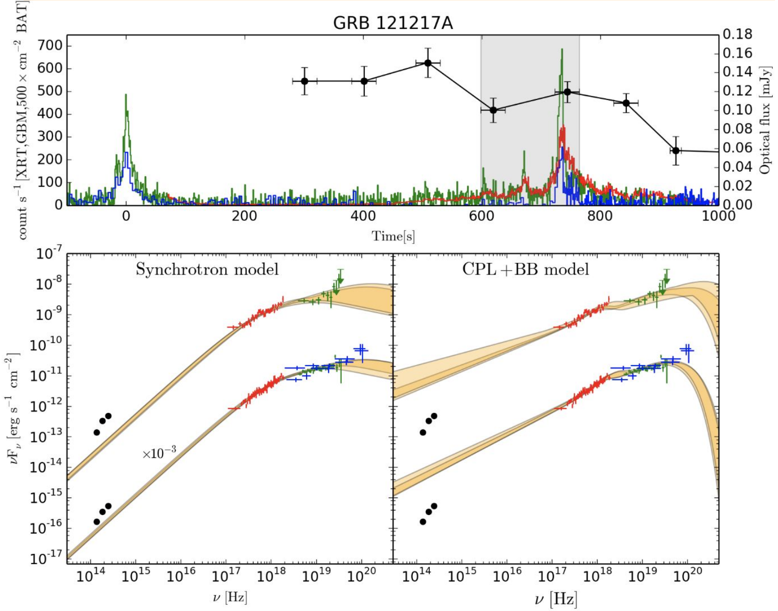
Spectral lag distribution for Swift/BAT short and long GRBs

Bernardini et al. 2015, MNRAS 446, 1129

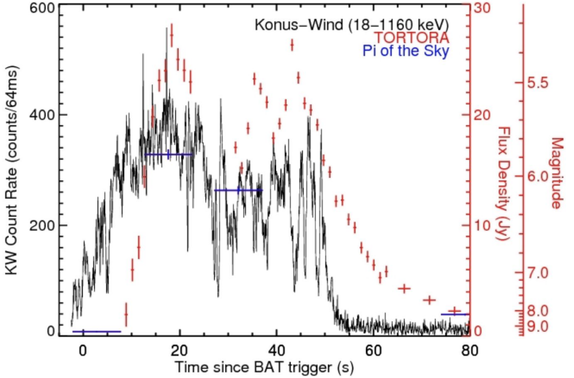
Joint analysis with multiple SVOM instruments

- **Prompt optical flash observed during the prompt emission (GRM+ECLAIRs+GWAC)**
  - Study of the optical variability and correlation with high energy → <u>constraints on the emission region</u>
- **Rapid broadband follow-up before the end of the prompt emission (GRM+ECLAIRs+MXT+C-GFT or F-GFT)**
  - Broadband SED analysis over 6 decades in energy → consistency with the optical flux put further <u>constraints to the low-energy tail of the spectral models</u>

Broadband SED analysis of simultaneous Fermi/GBM, Swift/BAT and XRT and optical data, comparing to different models. The extrapolation of the best-fitting models at higher-energy to the optical band in one case overestimated the observed flux, ruling out this model



The "naked-eye" GRB 080319B, where a bright optical flash was observed during the prompt emission. The broad consistency with the high-energy emission indicates that both originate from the same site



Racusin et al. 2008, Nature 455, 7210

Oganesian et al. 2019, A&A 628, A59