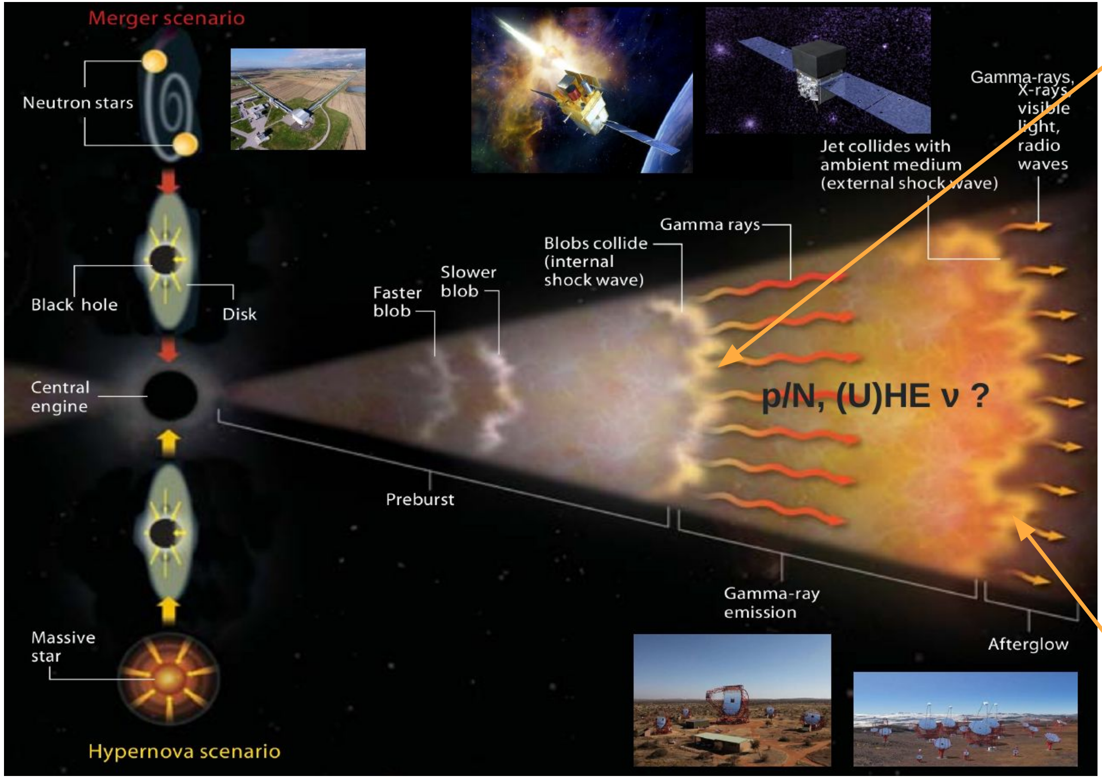
Focus on GRB prompt emission (and how to analyze it with SVOM)

Frédéric Piron
(CNRS/IN2P3/LUPM)

Maria Grazia Bernardini
(INAF/Brera Observatory)

SVOM Scientific Workshop, Xichang, June 2024

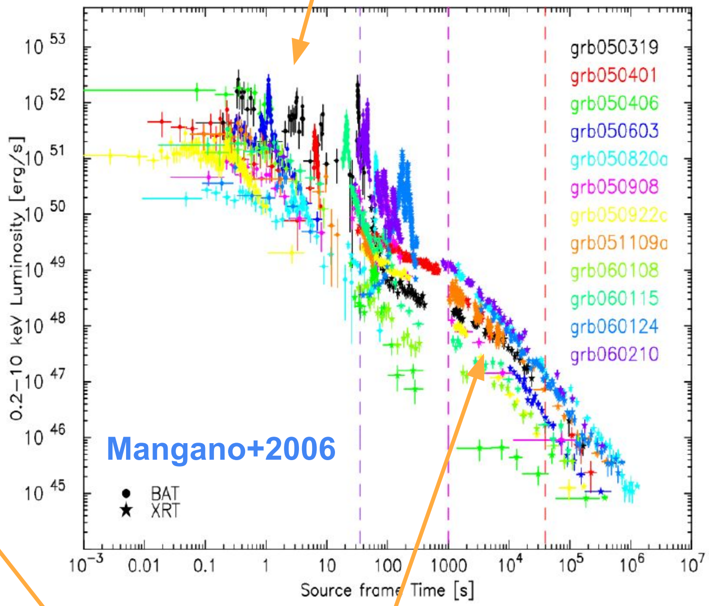
Internal vs. external emissions



Emission internal to the jet

- Highly intense and variable
- Produced at $R \sim 10^{14\text{-}15(16)}$ cm

→ observed **prompt** emission



Emission at external shock

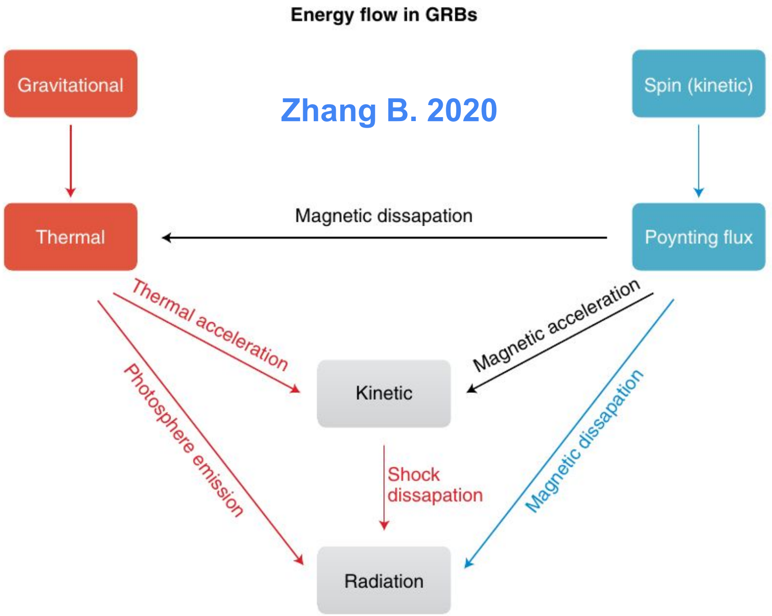
- Fainter, less erratic, decays rapidly
- Produced at $R \sim 10^{16\text{-}17}$ cm

→ observed **afterglow** emission

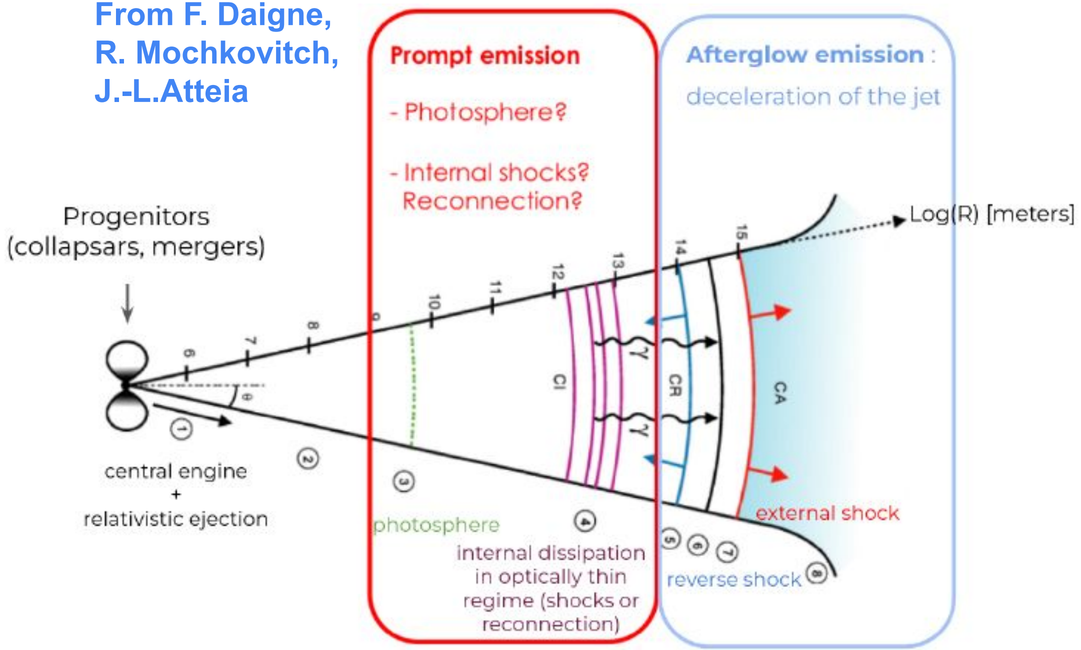
Somewhat simplified view:

- Prompt = "early", not always internal to the jet, for instance GeV external shock emission can start during keV-MeV prompt phase
- Role of reverse shock

Model classes for GRB prompt emission



Zhang B. 2020



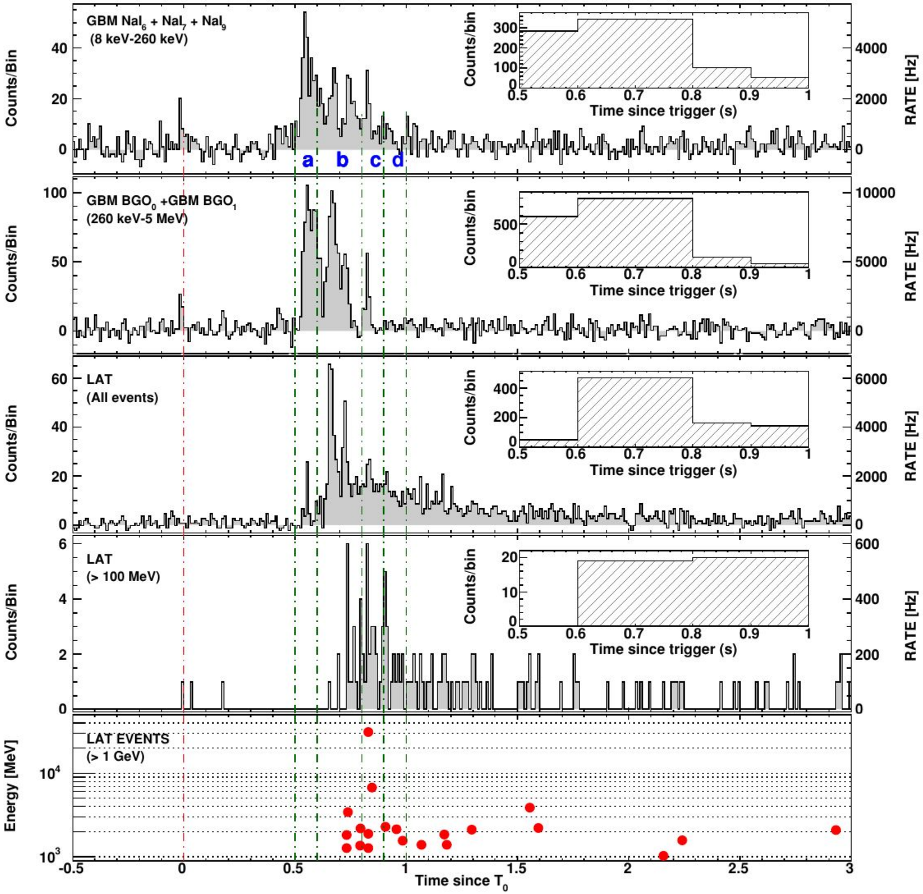
From F. Daigne, R. Mochkovitch, J.-L.Atteia

- **Fireball**
  - Jet thermal acceleration, then dissipation (accelerated electrons) in internal shocks
  - Non-thermal emission + bright photospheric quasi-thermal emission

- **Magnetized jet**
  - Jet magnetic acceleration, then dissipation in internal shocks or via magnetic reconnection
  - Non-thermal emission (+ weak photospheric quasi-thermal emission?)

Multi-band/multi-detector light curve

- **Count 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 LC for pre-defined sub-energy bands
  - Time binning appropriate to the characteristics of the GRB (total duration, temporal variability, ..)
- **Preliminary considerations from the LC**
  - Define the main emission episodes, pulses
  - Presence of a precursor?
  - Help define time intervals relevant for the spectral analysis

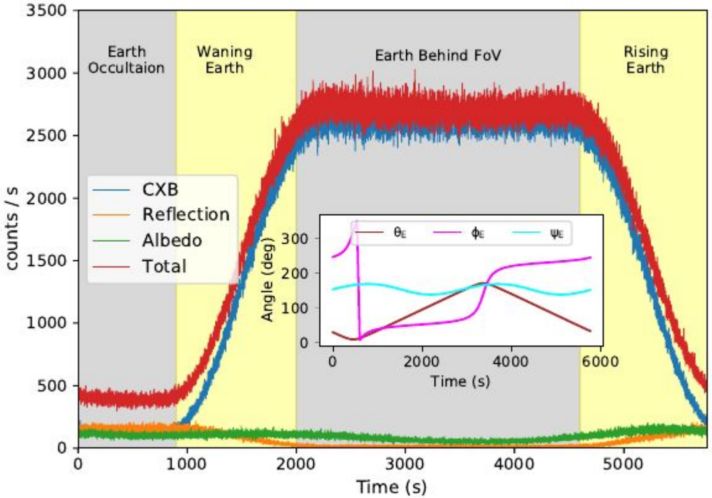


Ackermann+2010

Count LC of GRB 090510 prompt emission in different energy bands as observed by Fermi/GBM and LAT

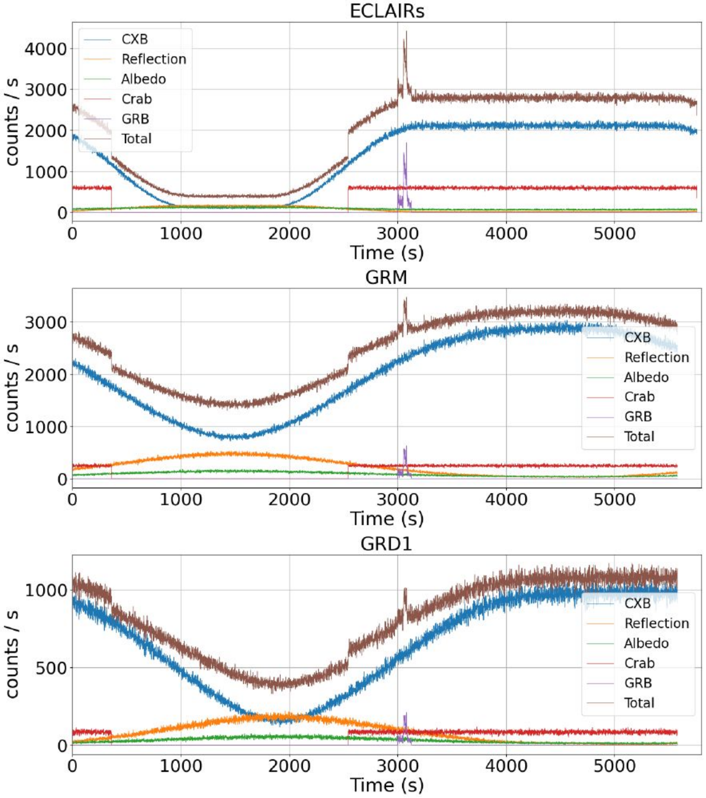
Modeling background variations in ECLAIRs & GRM

- **Model T (“time”): pol(t) → simplistic**
  - For slow bkg variations (e.g. not in case of slew)
- **Model E (“Earth”): pol[cos(Θ_{Earth}(t))] → use Earth position in FoV**
  - For basic temporal analysis
- **Model P (“physical”): integrate the contributions from the bkg components (CXB, Earth reflection and albedo) over FoV**
  - For any temporal or spectral analysis
  - GEANT4 simulations to be validated against real data (EIC task)



ECLAIRs count LC during 1 orbit (bkg only)

Mate+2019
S. Mate thesis 2021
B. Arcier thesis 2022
A. Maiolo thesis 2023

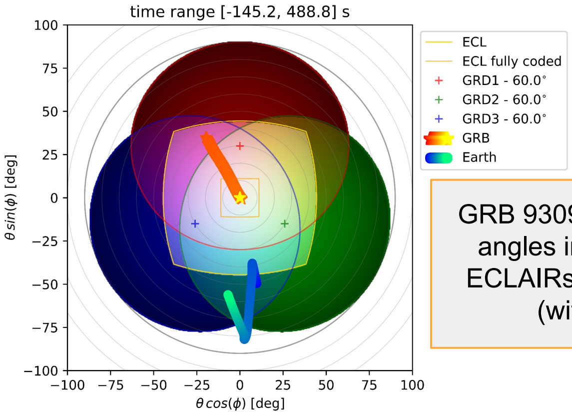


Count LC (ECLAIRs, GRM, GRD1) during 1 orbit in the Crab direction: backgrounds, 1 GRB, Crab nebula

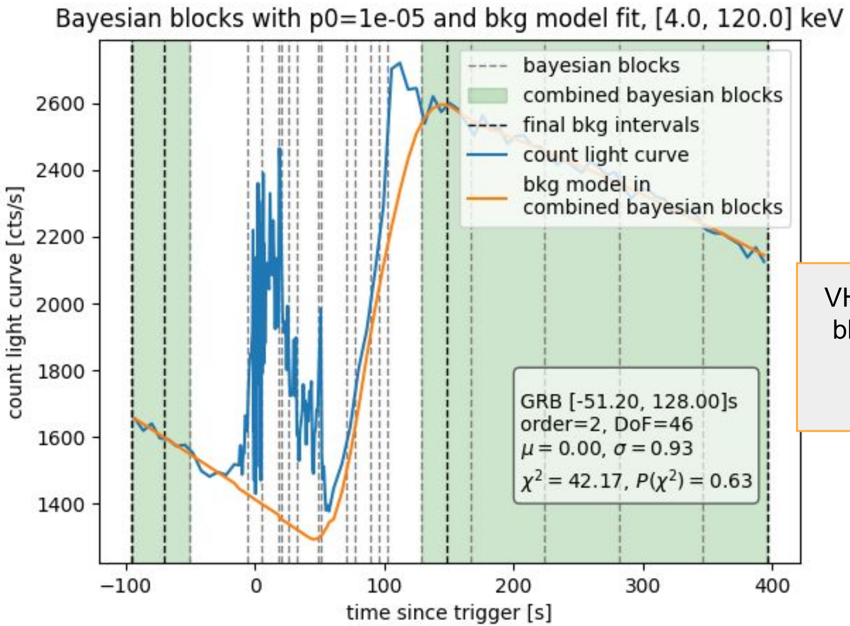
Fitting background variations (1/2)

- **Needed if no imaging possible**
  - GRM temporal & spectral analysis
  - ECLAIRs VHF LC analysis
- **Define the 2 bkg regions (pre/post burst)**
  - Bayesian blocks + optimization of bkg regions & model
- **Here below: bkg model E**

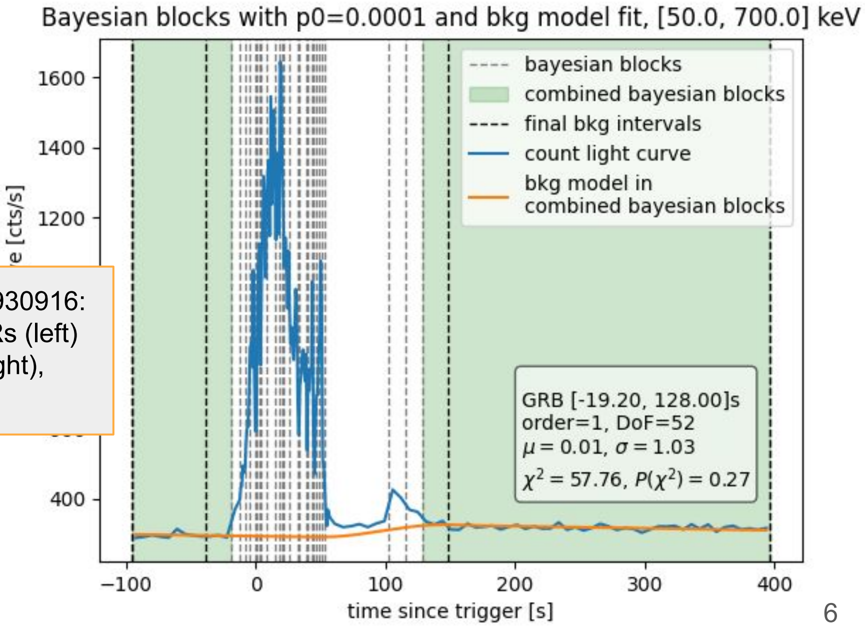
From J. Wang (IAP)



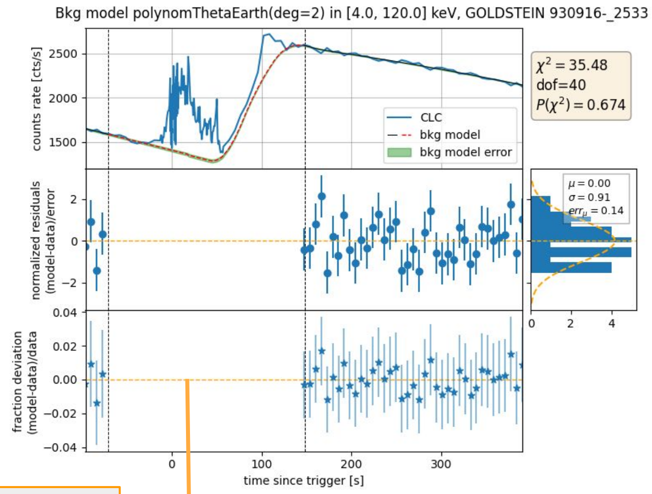
GRB 930916 and Earth angles in the FoV of ECLAIRs & GRD1,2,3 (with slew)

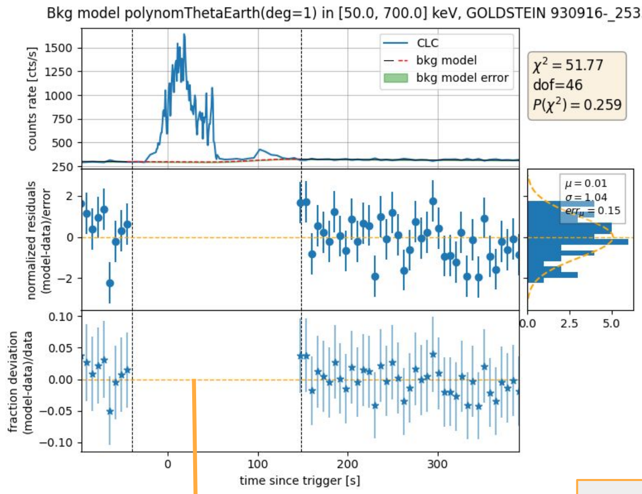


VHF LC of GRB 930916: bkg fit in ECLAIRs (left) and GRD1 (right), with slew



Fitting background variations (2/2)



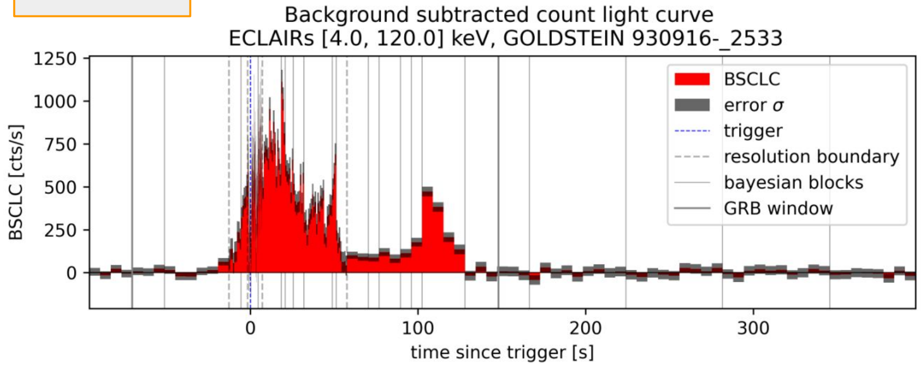


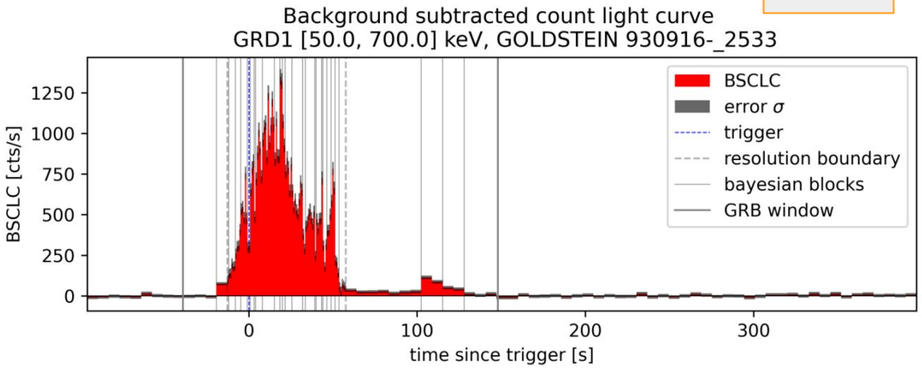
From J. Wang (IAP)

VHF LC of GRB 930916: bkg fit (top) and bkg-subtracted LC (bottom) in ECLAIRs (left) and GRD1 (right)

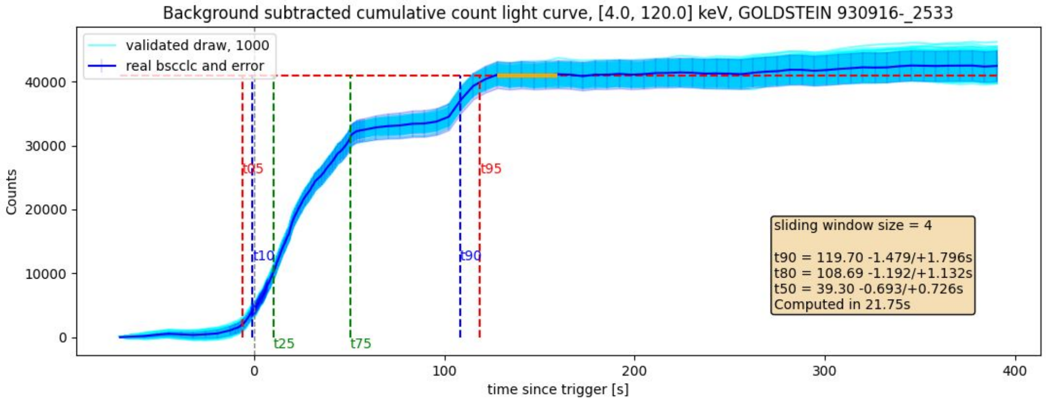
ECLAIRs

GRD1

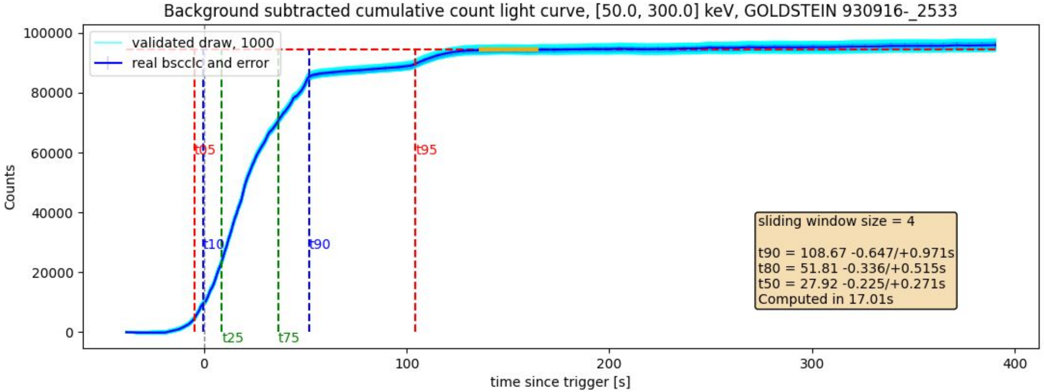




Observed durations

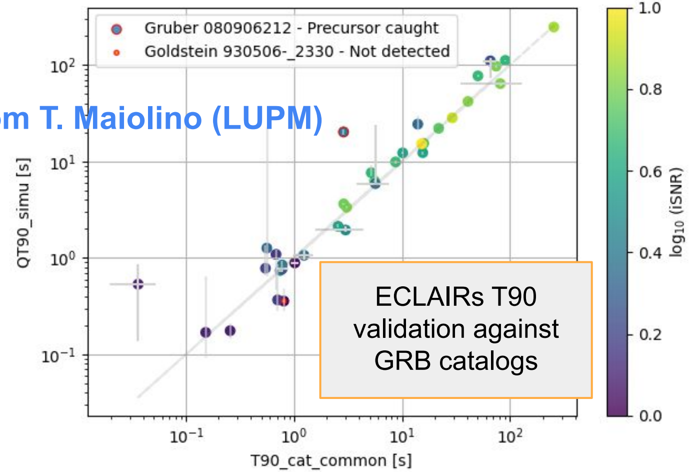


GRB 930916 durations from bkg-subtracted cumulative count LC in ECLAIRs (top) and GRM (bottom)



- **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 depends on SNR (intensity and detector sensitivity) → lower limit on GRB duration**

From T. Maiolino (LUPM)



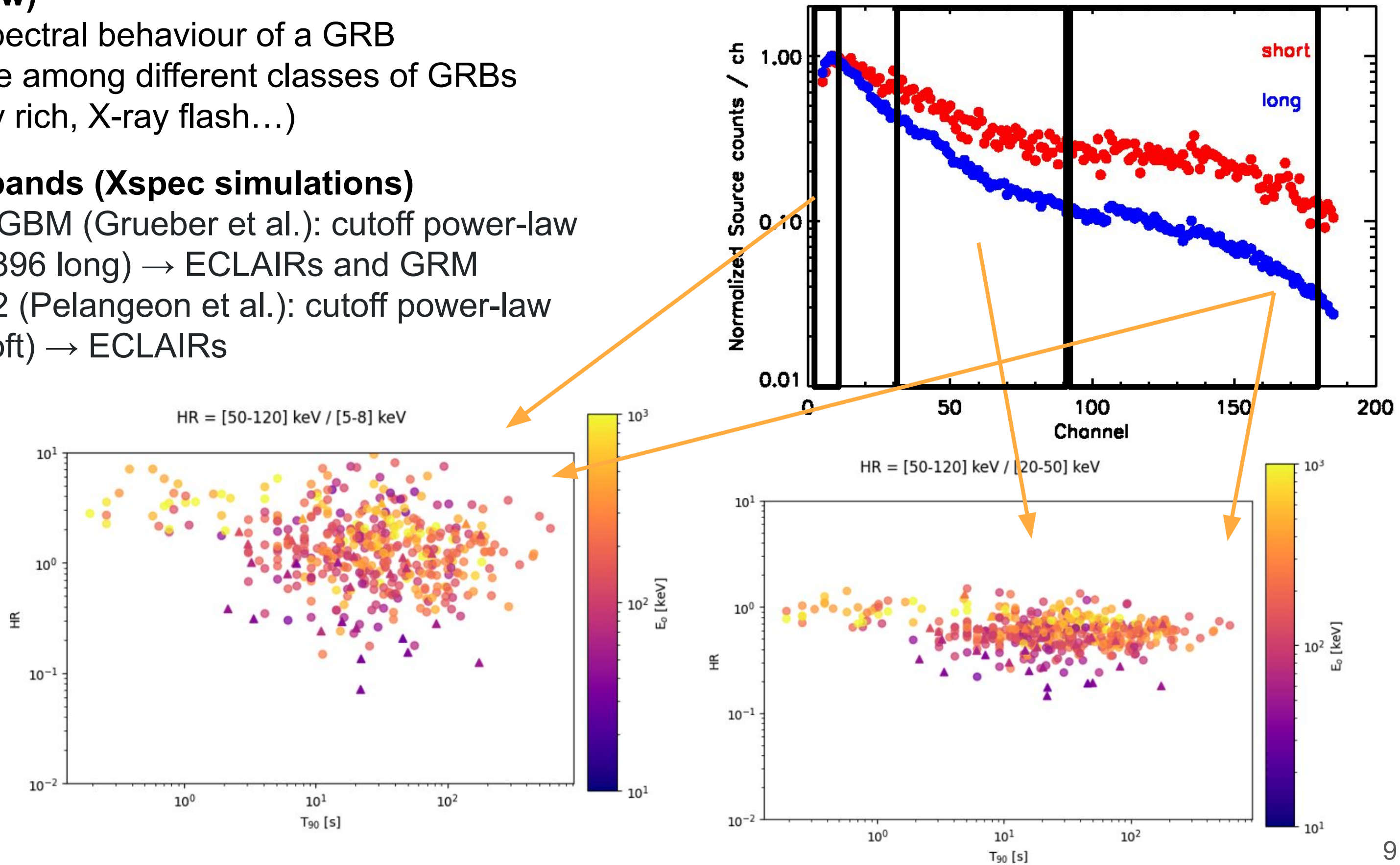
ECLAIRs T90 validation against GRB catalogs

Hardness Ratio(s)

- **HR: ratio between the number of GRB counts in two energy bands (usually high/low)**
  - Indicator of the spectral behaviour of a GRB
  - Helps discriminate among different classes of GRBs (short, long, X-ray rich, X-ray flash…)

- **Choice of HR energy bands (Xspec simulations)**
  - Catalog of Fermi/GBM (Grueber et al.): cutoff power-law model (50 short, 396 long) → ECLAIRs and GRM
  - Catalog of HETE2 (Pelangeon et al.): cutoff power-law model (45 long/soft) → ECLAIRs

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



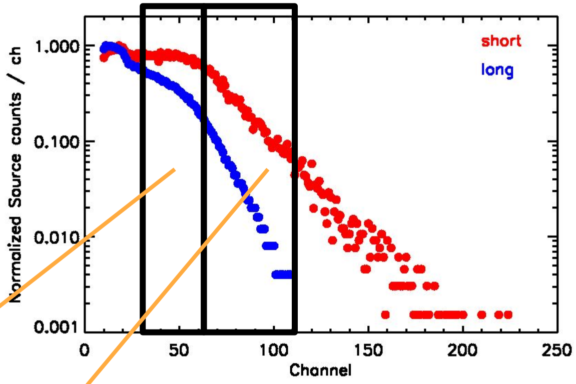
From M.-G. Bernardini

HR vs. T90 for the Fermi/GBM (points) and HETE2 (triangles) catalogs simulated with ECLAIRs

Hardness Ratio(s)

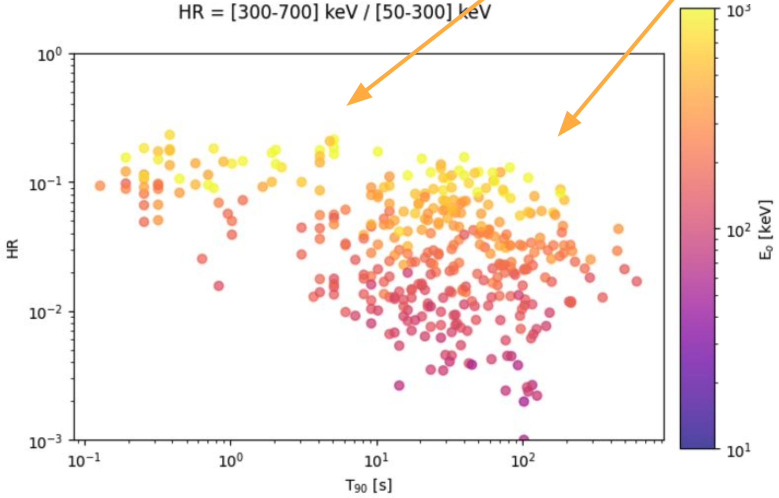
- **HR: ratio between the number of GRB counts in two energy bands (usually high/low)**
  - Indicator of the spectral behaviour of a GRB
  - Helps discriminate among different classes of GRBs (short, long, X-ray rich, X-ray flash…)
- **Choice of HR energy bands (Xspec simulations)**
  - Catalog of Fermi/GBM (Grueber et al.): cutoff power-law model (50 short, 396 long) → ECLAIRs and GRM
  - Catalog of HETE2 (Pelangeon et al.): cutoff power-law model (45 long/soft) → ECLAIRs

GRM (GRD1) normalized mean count spectra for simulated long and short GRBs from Fermi/GBM catalog



From M.-G. Bernardini

HR vs. T90 for the Fermi/GBM (points) catalog simulated with GRM (GRD1)

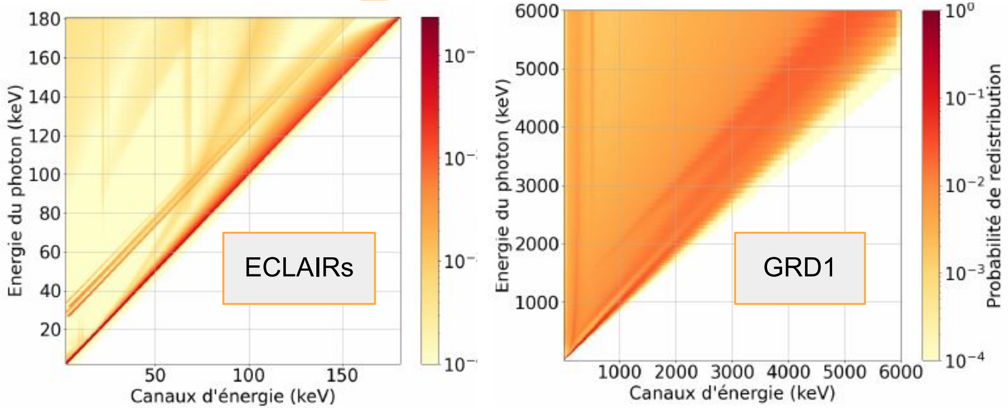


Spectral analysis : methodology

- **Number of detected counts between E'_{min} and E'_{max} (measured energy):**

$$C(E'_{\rm min}, E'_{\rm max}) = T_{\rm obs} \int_{E'_{\rm min}}^{E'_{\rm max}} dE' \int_0^{+\infty} dE\, f(E)\, A_{\rm eff}(E, \theta, \phi)\, D(E, E') + B(E'_{\rm min}, E'_{\rm max})$$

- **Photon spectrum f(E) [ph/cm²/s/keV]**
  - E is the true photon energy
- **Effective detection area Aeff(E, θ, φ) [cm²]**
- **Energy redistribution D(E,E') [keV^{-1}]**



- <u>**Forward-folding spectral analysis: assume a spectral model f(E)**</u> **and fold it with the detector response**
  - Because energy dispersion can not be easily inverted / corrected (especially for GRM)
- <u>**Maximize the likelihood**</u> **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

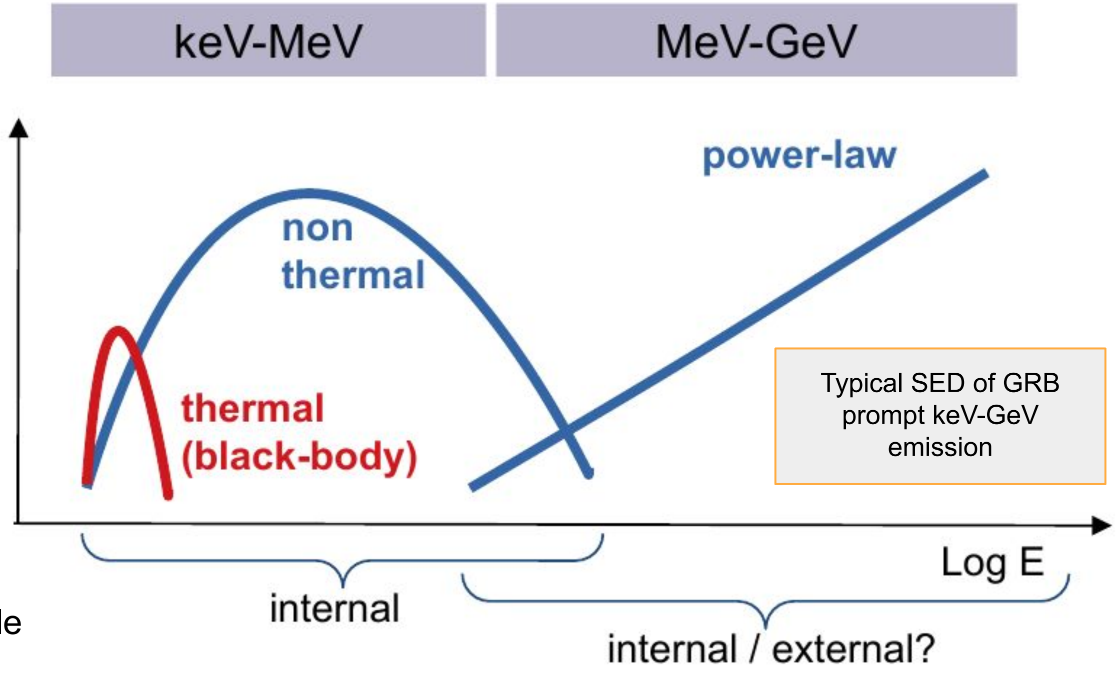
Spectral components

- **<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**
- **Variability is key to differentiate internal from external emission spectral components**

Phenomenological spectral models f(E)

For a preliminary characterization of GRB prompt emission spectrum

- [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)
- …

$$f_{PL}(E) = A\left(\frac{E}{E_{piv}}\right)^{\alpha}$$

Nested models:

- Band → CPL when β → – inf
- CPL → PL when Ep → + inf

$$f_{COMP}(E) = A\left(\frac{E}{E_{piv}}\right)^{\alpha} \exp\left[-\frac{E(2+\alpha)}{E_p}\right]$$

Band+1993

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

Physical spectral models f(E)

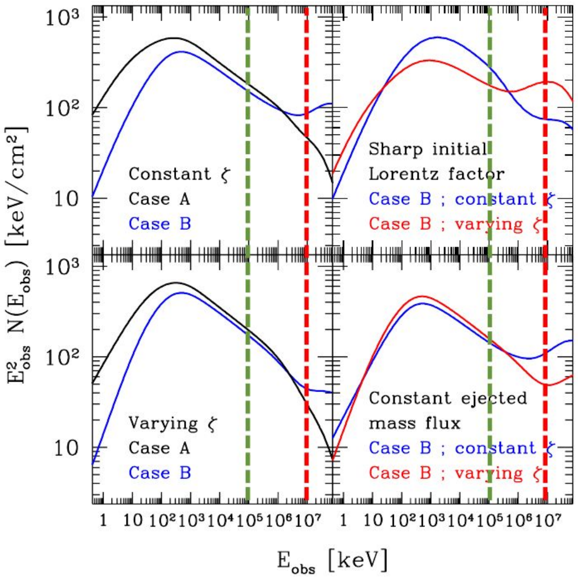
To infer the physical parameters of GRB prompt emission

- [2 params] Black-Body (BB) or relativistic photosphere
- Synchrotron from a population of accelerated electrons Zhang B.B. +2016, Burgess+2019, Oganesyan+2019, Ronchi+2020
- **Internal-Collision-induced MAgnetic Reconnection and Turbulence (ICMART)** Zhang B. +2011
- **GRB internal shock synchrotron**
  - E_k, ζ, $ε_e$, $ε_B$, p, etc Bosnjak+2009, Daigne+2011 Bosnjak+2014

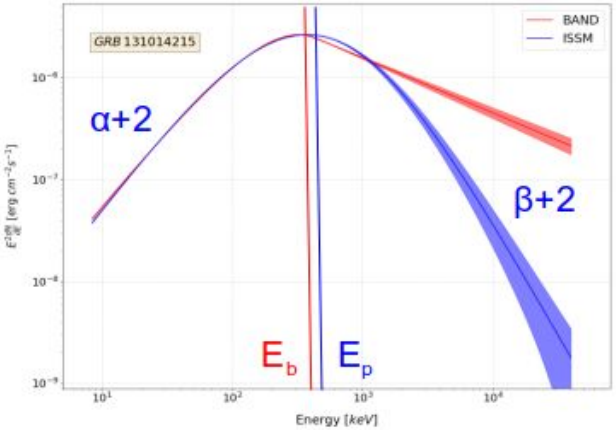
$$f_{BB}(E) = \frac{A \times 8.0525\, E^2}{(kT)^4\,[\exp(E/kT) - 1]}$$

- Proxy function **ISSM : α, β, Ep, norm**
  - **Internal Shock Synchrotron Model**
  - Continuously curved unlike Band
  - Better fits than Band
  - ISSM → CPL when β → – inf

Yassine+2020
Scotton+2024, in prep



SED of Fermi/GBM GRB 131014A:
Band vs. ISSM models



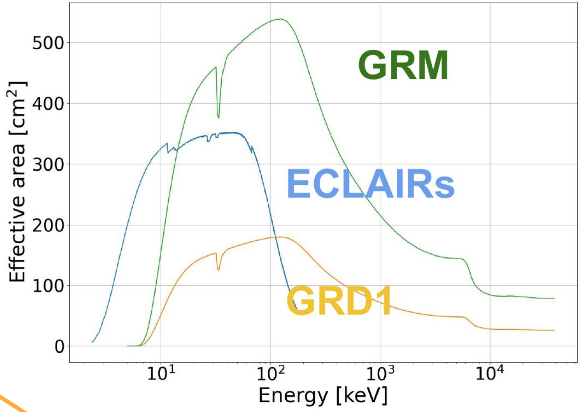
$$f_{\mathrm{ISSM}}(E) = \frac{A}{\left[1 - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}} \times \left(\frac{E}{E_r}\right)^{\alpha}\left[\frac{E}{E_r} - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha},$$

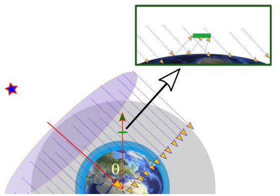
Effective detection area

$$A_{\mathrm{eff}}(E,\theta,\phi) = A_{\mathrm{eff}}(E,\theta=0°) \times \epsilon(E,\theta,\phi)$$

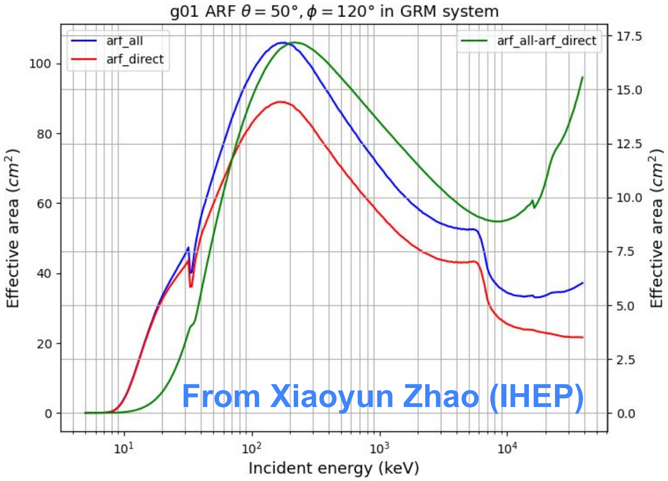
- **On-axis effective detection area $A_{eff}(E, \theta=0°)$**
- **Off-axis efficiency $\varepsilon(E, \theta, \varphi)$ ~ cos(θ)**
  - ECLAIRs blocking photons for GRD2 at θ>60°
- **Origins of GRB photons in GRM:** directly incident, scattered in SC, or scattered by atmosphere (~20 to ~200 keV)

On-axis effective detection area for ECLAIRs, GRM and GRD1

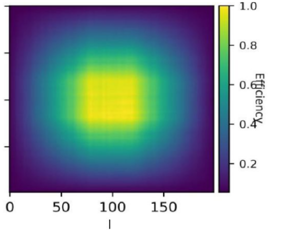




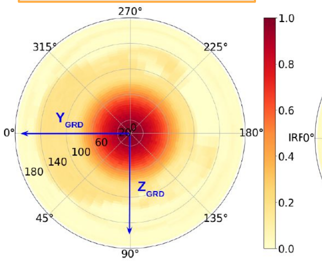
GDR1 direct vs. indirect A_{eff}

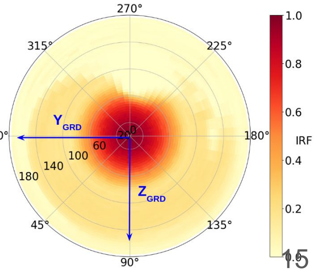


ECLAIRs eff. at 20 keV

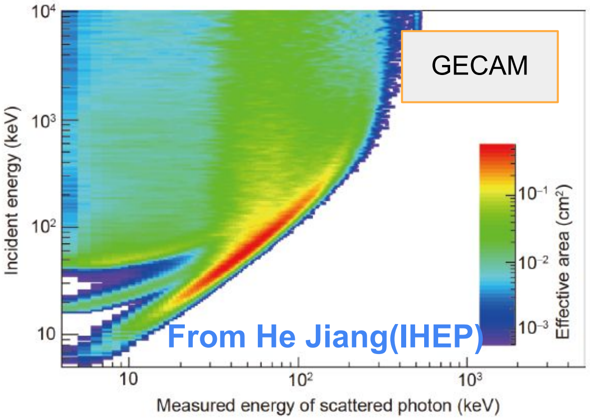


GRD1 & GRD2 eff. at 100 keV





GECAM



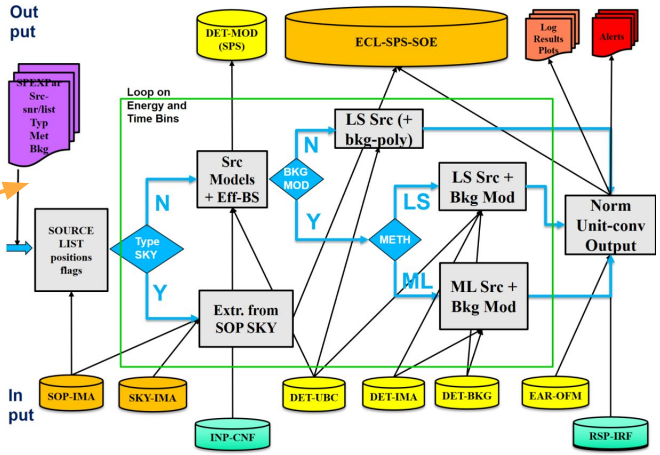
Spectral analysis : preparation

Define energy channels: pseudo-logarithmic, follow energy resolution
Then, for each time interval (emission episode, pulse, etc) to be analyzed:

Make count spectra from calibrated events (GRM-EVT & ECL-EVT-CAL)

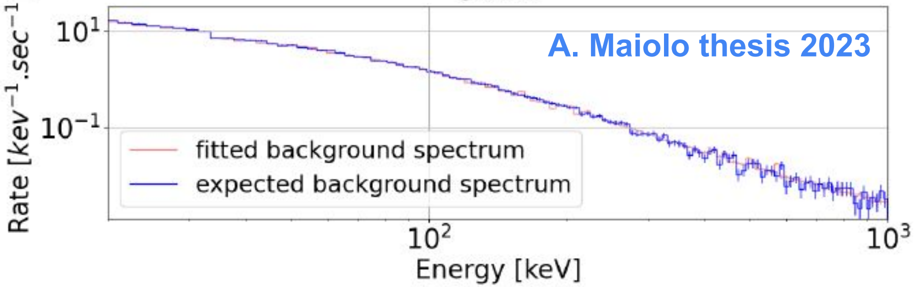
- Imaging technique (ECLAIRs): fit the shadowgram in each energy channel to extract the GRB count spectrum (GCSP, bkg subtracted)
  - Using the ECLAIRs pipeline at FSC: complex machinery
- Counting technique (GRM, possibly ECLAIRs): in each energy channel,
  - CSP: total count spectrum (bkg + GRB) in time interval
  - BCSP: fit bkg in 2 LC regions and extrapolate to time interval

FSC ECLAIRs pipeline (ECPI): workflow of the module for source product extraction



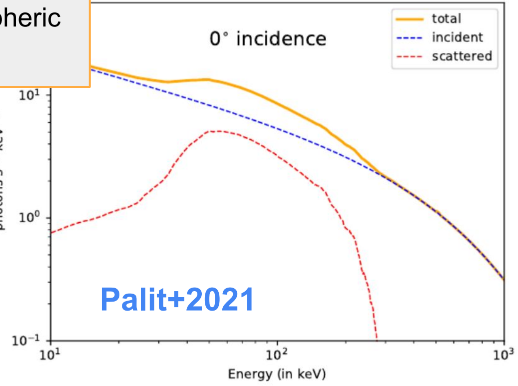
From A. Goldwurm (APC)

GRD2 bkg count spectrum (BCSP) during a slew: simulated spectrum (blue) v.s. fitted with bkg model P (red)



A. Maiolo thesis 2023

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



Palit+2021

Make detector response matrices from instrument CALDBs

- GRM: account for GRB photons scattered by Earth atmosphere
  - If not included, can mimic fake spectral component

Spectral analysis : procedure

- **For instance with (py)XSPEC**
  - Load count 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 statistic among variants of -2*log[L(D|M)]: *cstat*, *pgstat*, *chi* (see Statistics in XSPEC)
  - Fit → f(E) parameters and their covariance matrix
  - Assess fit quality from residuals & goodness of fit (e.g. chi² prob.)

- **The discussion of the quality of the fitting should focus on:**
  - whether the form of the likelihood function is appropriate
  - how well the model count spectra are calculated

- **Exercise your own judgement (the count 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

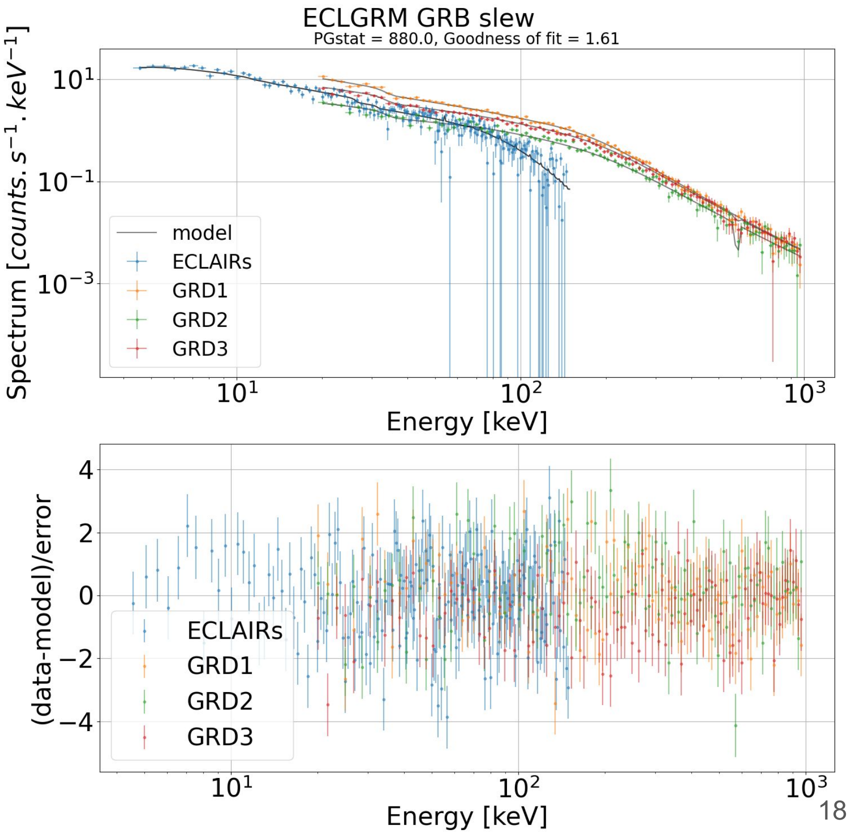
Spectral fit display : good practices

- **How to present the results in a convincing way that is not misleading?**

- **General approach: treat the data counts as holy and unchangeable**
    - They do not depend on assumed models
    - To some extent, they do not depend on detector response functions
        - They could change after some detector re-calibration and data reprocessing
    - They get one as possible to the unvarnished “truth”

- **<u>Fit displays should show count spectra [counts/s/keV]</u>**
    - and compare them to model counts

GRB count & model spectra + residuals for a joint ECLAIRs + GRM spectral fit (with slew)



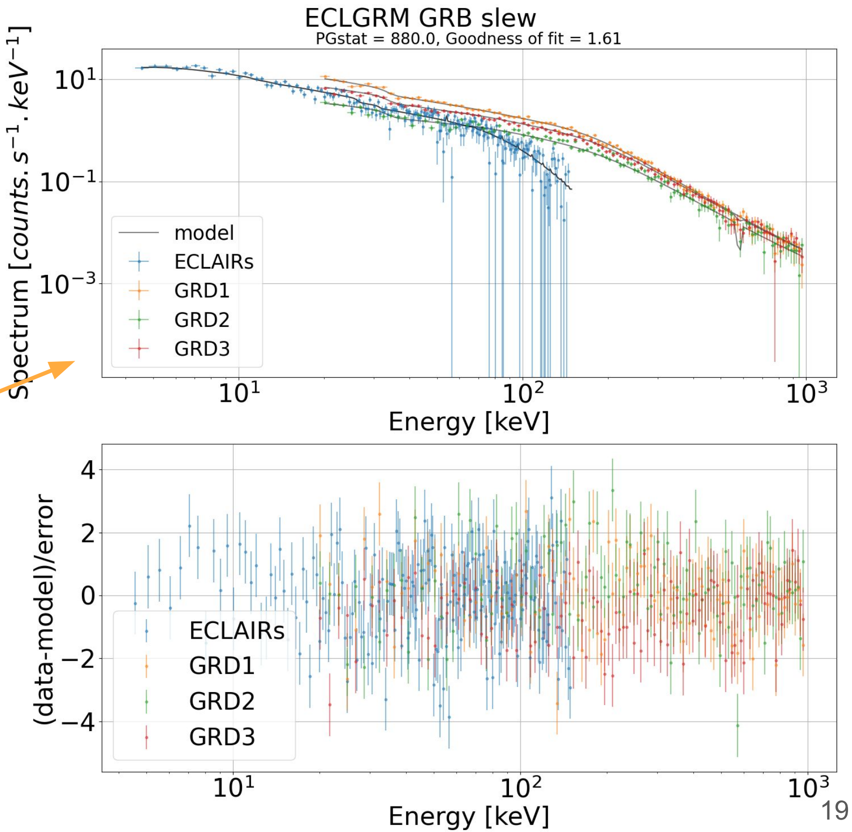
Spectral fit examples : ECLAIRs + GRM

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

A. Maiolo 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 count & model spectra + residuals for a joint ECLAIRs + GRM spectral fit (with slew)



Spectral fit display : a bad practice

- **Do not use the XSPEC setplot area display, nor plot ufspec**
  - They try to prettify the count spectrum by rescaling the counts Ci in each energy channel: Ci → Ci * (model) / (folded model)
    - Units: [counts/s/keV/cm²] or [erg/cm²/s]

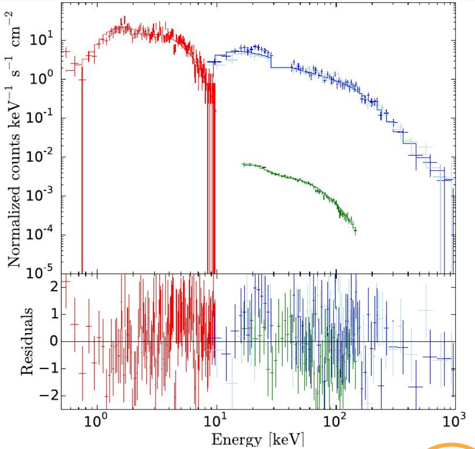
- **Wrong, unless the energy dispersion effect is negligible**

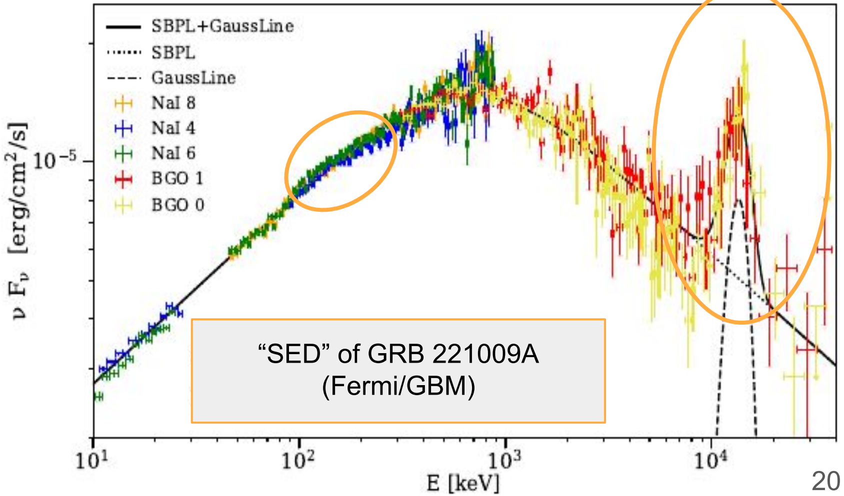
- **Y axis: you think you're looking at the true spectrum, but you are not!**
  - Features (bumps, wiggles) are still there!

- **X-axis: still measured energies, not photon true energies**
  - A spectral cut-off will appear very different from what has been actually fitted
  - A spectral line will still be broadened

- **Meaningless flux "points", misleading, potentially harmful**
  - People could be encouraged to take these values as real data points that can be used in a fit to a flux model
    - and they might find different results!

"Normalized" count spectra of GRB 140108A in Swift (XRT, BAT) and Fermi (GBM)





"SED" of GRB 221009A (Fermi/GBM)

Comparing spectral models (1/2)

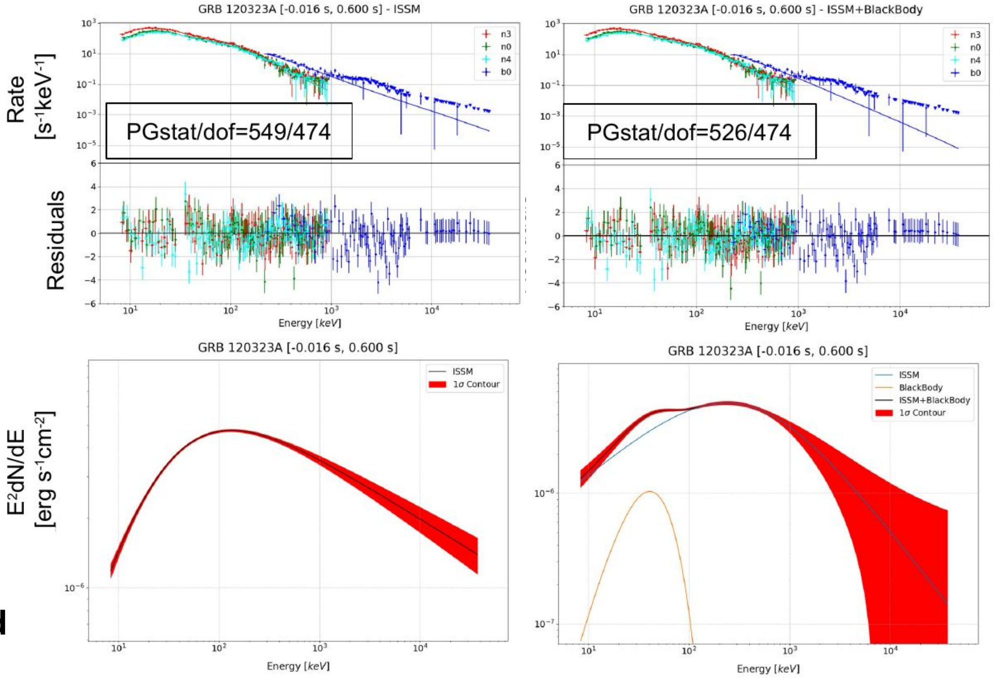
- **Increase gradually the model complexity**
  - E.g. PL → CPL → Band or ISSM
  - Add new components if suggested by residuals

- **Choose between 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

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

- **True spectrum: SED confidence contours obtained by sampling the best spectral parameters**

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



L. Scotton thesis 2023
Scotton+2024, in prep

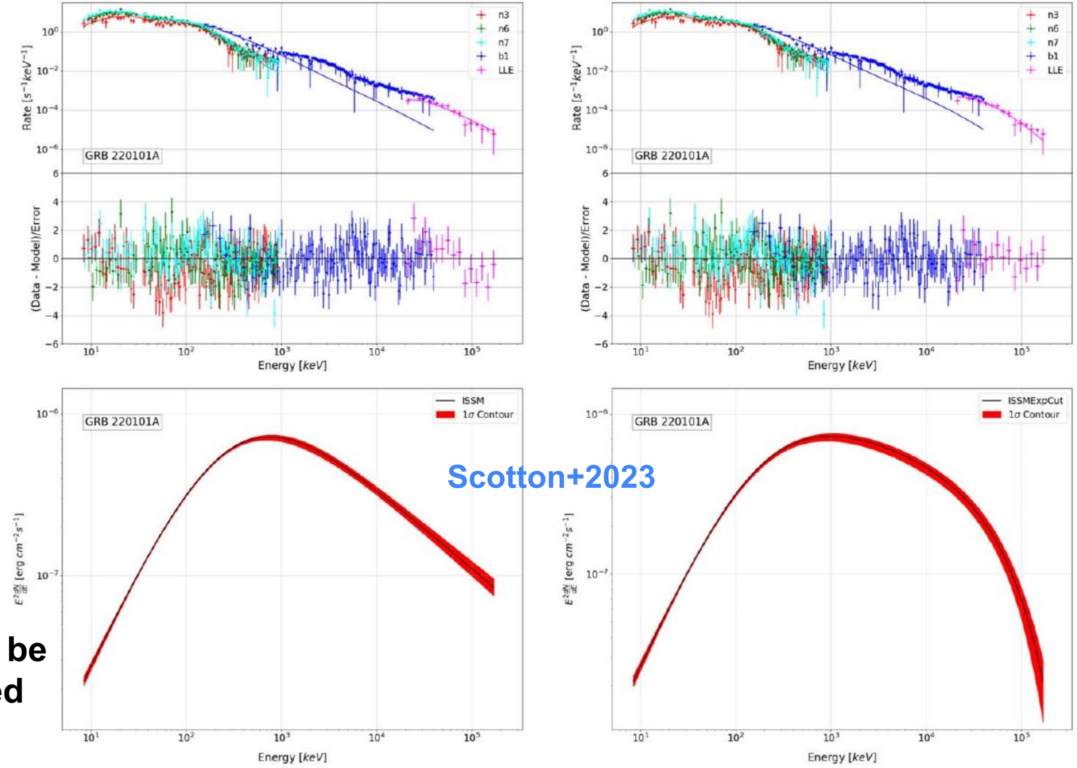
Comparing spectral models (2/2)

- **Models that appear very similar in data space can show different SED due to the effect of energy dispersion**

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**

- **True spectrum: SED confidence contours can be shown, always stating the model that was used**

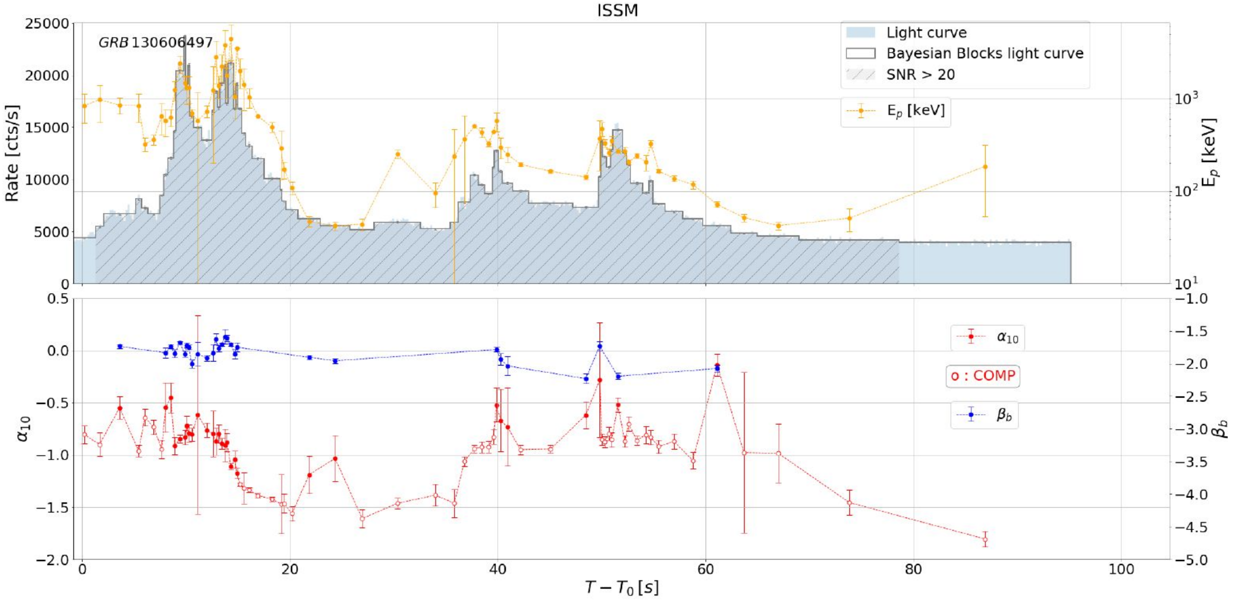
Fermi GRB 220101A high-energy spectral cutoff: fits, residuals and SED with ISSM (left) and ISSM * ExpCut (right)



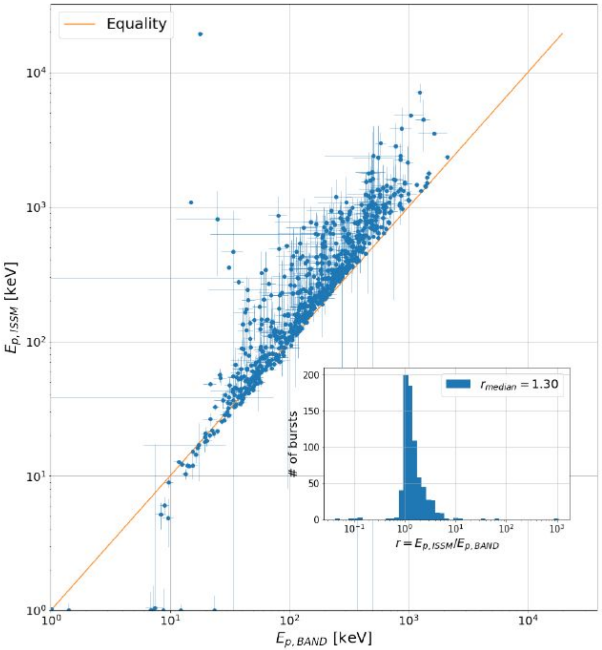
Scotton+2023

Time-resolved spectral 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 thesis 2023
Scotton+2024, in prep

Physical quantities derived from spectral analysis

- **Once the best spectral model f(E) is chosen in a given time interval (Δt), compute:**
  - The photon (energy) flux p (f) in a given energy band $[e_1,e_2]$:

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

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

  - The photon (energy) fluence:

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

- **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}:

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

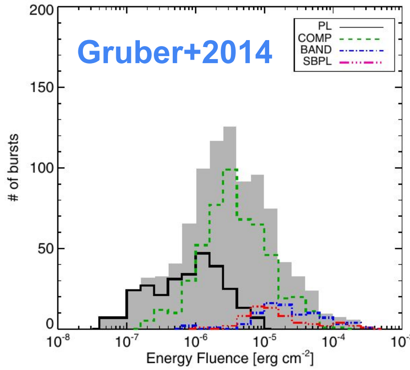
$$E_{iso} = \frac{4\pi d_l(z)^2}{(1+z)\Delta t} \int_{1/(1+z)\,keV}^{10^4/(1+z)\,keV} E\, f(E)dE \quad [erg]$$

Bloom+2001
Amati+2002

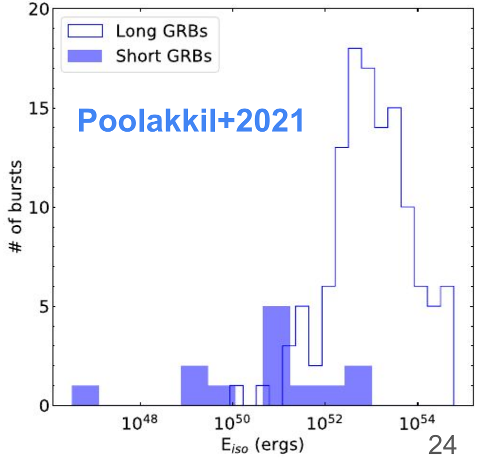
stating the cosmological model used for the luminosity distance

- **Compute errors by sampling the best spectral parameters**

Fermi/GBM (4 yrs)
10 keV - 1 MeV



Fermi/GBM (10 yrs)

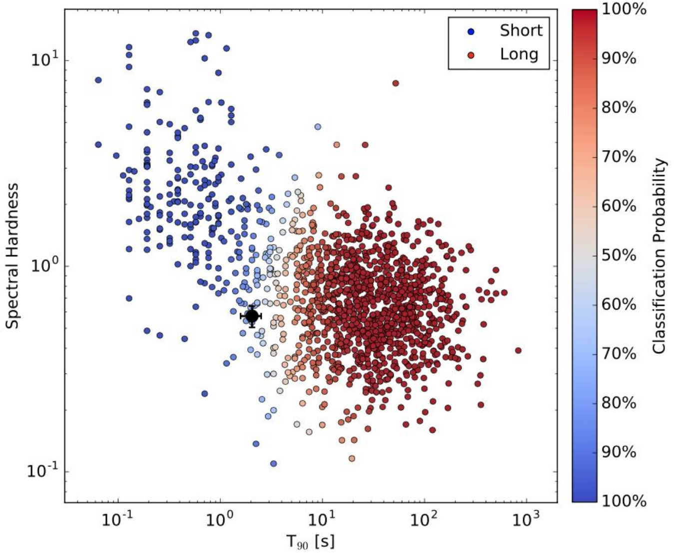


Comparing the GRB properties with the GRB populations

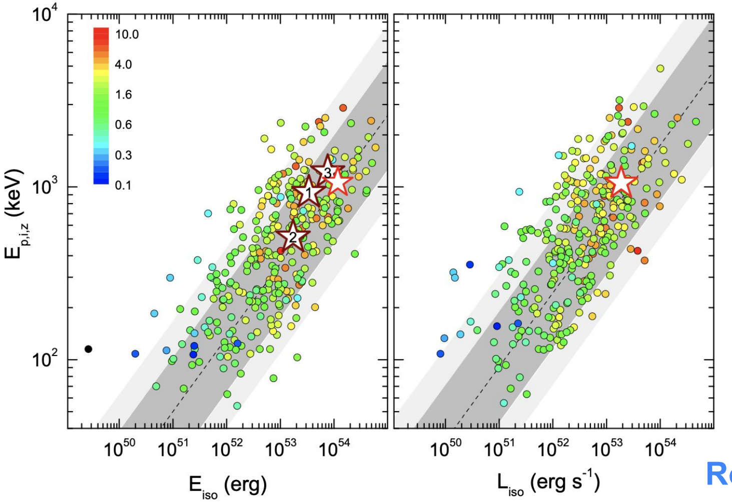
The temporal and spectral analysis of the prompt emission provides a set of physical quantities that can be used to characterise the GRB with respect to the known populations of GRBs

- **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 **Rastinejad+2022, Rossi+2022**
  - Ultimately identify the nature of the progenitor

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+2017



Rest-frame energetics of the high-z GRB 210905A (star) in the Amati (left) and Yonetoku (right) planes (long GRB correlations in grey, with z color gradients)

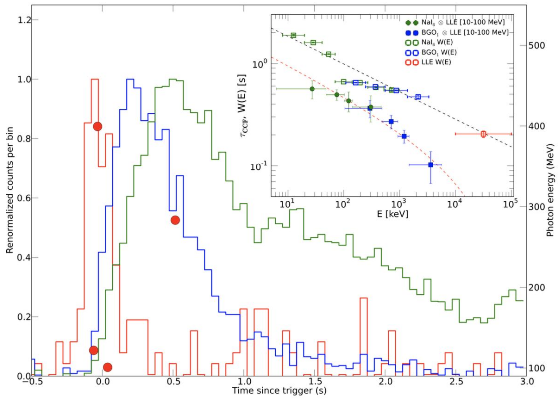
Rossi+2022

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 LC 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+2001
- **Pulse width vs. energy w(E)**
  - Low energy pulses are wider than high energy pulses: w ~ E^{-a} with a~0.4 Norris+1996
- **Minimum variability timescale with significant flux variation**
  - Structure Function (SF) estimator Golkhou+2014, 2015
  - Used to estimate the size of the emitting region

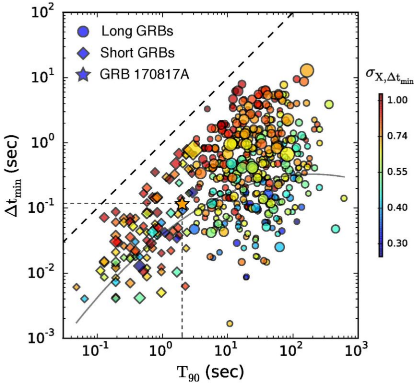
Composite normalised LC in different energy bands of the very bright GRB 130427A from Fermi/GBM and LAT. Inset: Lag and pulse width analysis.

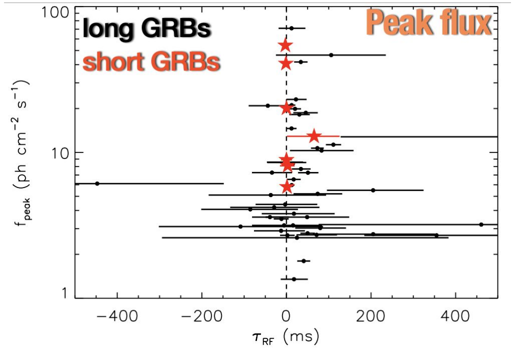


Preece+2014

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

Goldstein+2017

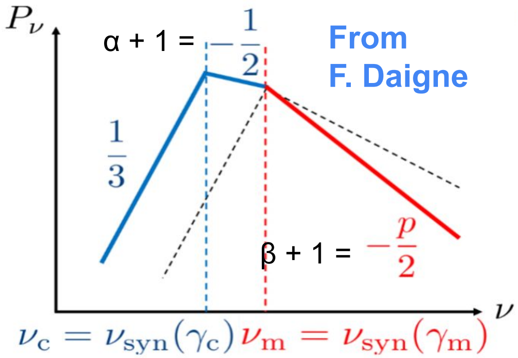




Spectral lag distribution for Swift/BAT short and long GRBs

Bernardini+2015

Synchrotron interpretation of the keV-MeV prompt emission



From F. Daigne

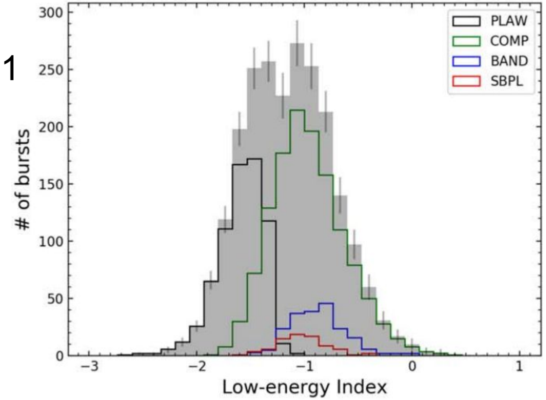
Theory

- High luminosity implies very efficient synchrotron emission (fast-cooling)
- Standard expectations: α = -3/2 and β = -p/2 - 1
- Maximum value: α < -2/3 (slow-cooling)

Observations

- α > -3/2, and > -2/3 for ~10-20% of GRBs
- So-called "synchrotron line-of-death problem"
- (but see discussion in **Burgess+2019**)

Fermi/GBM (10 yrs)



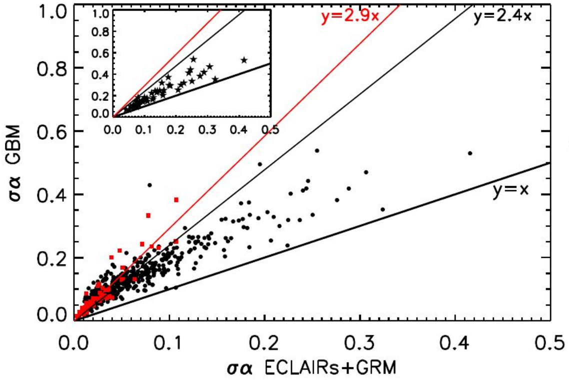
Poolakkil+2021

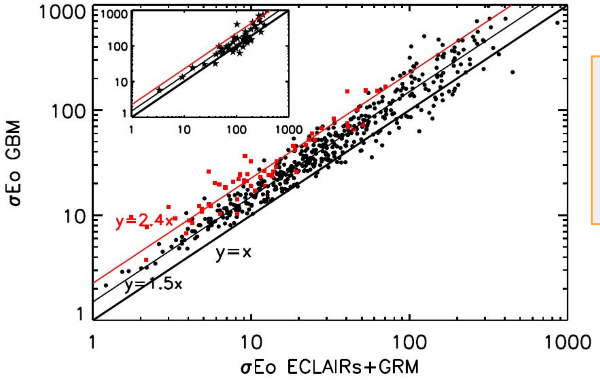
ECLAIRs+GRM will provide accurate spectral measurements at low energy

- Spectroscopic performance at least as good as Fermi/GBM
- Provided that the two instruments are well cross-calibrated in flight

Fermi/GBM vs. SVOM/ECLAIRs+GRM : error on the low-energy spectral index α

Bernardini+2017

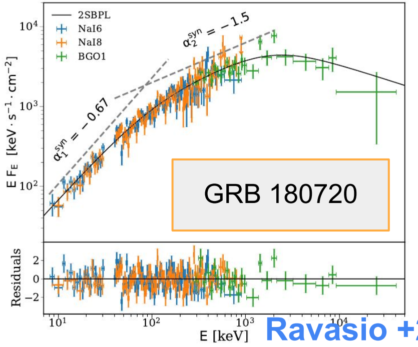


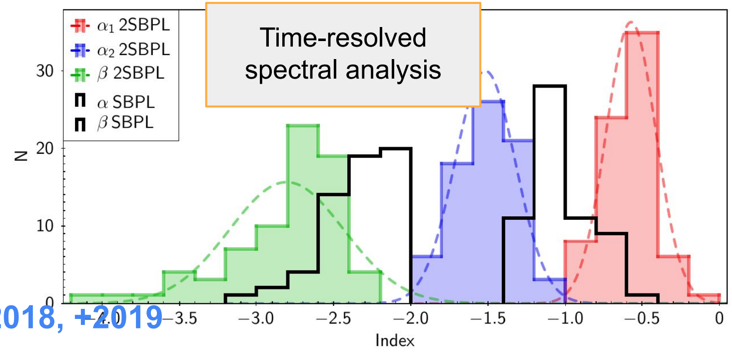


Fermi/GBM vs. SVOM/ECLAIRs+GRM : error on the characteristic energy E0 = Ep / (2+α)

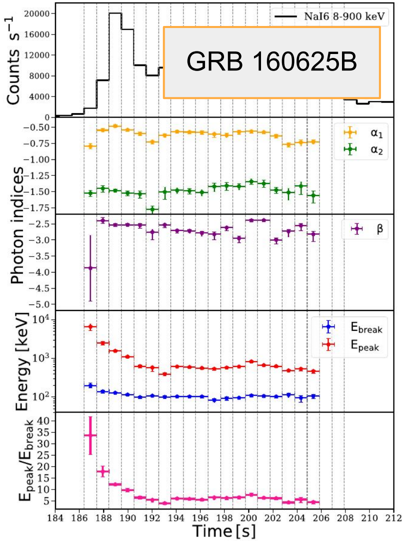
Synchrotron interpretation of the visible-to-MeV prompt emission

Out of the 10 Fermi/GBM brightest LGRBs, 8 have low-energy breaks



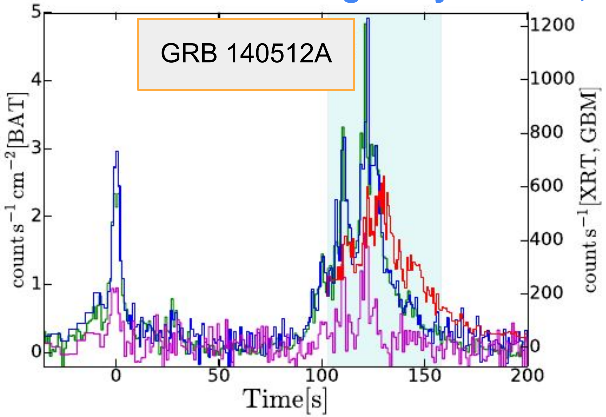


Ravasio +2018, +2019

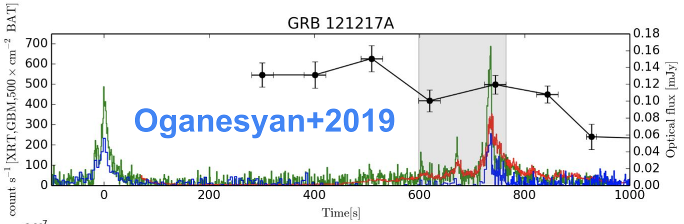


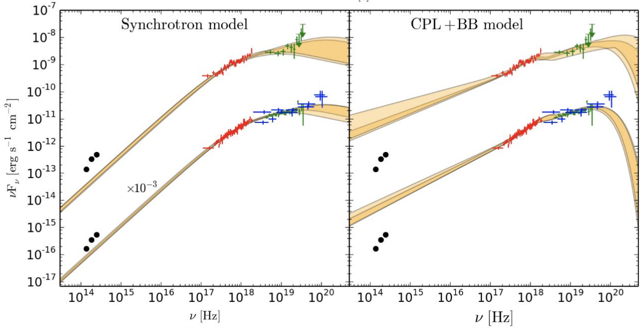
Sometimes long emission + rapid slew → XRT + BAT + GBM joint analysis possible

Oganesyan+2017, +2018



Sample of 21 GRBs with simultaneous Fermi/GBM, Swift/BAT, Swift/XRT and visible data. Synchrotron model provides good fits.





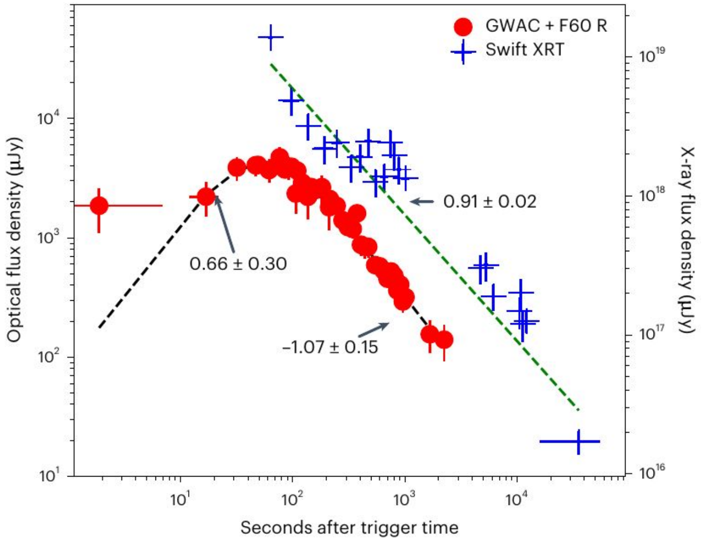
SVOM (GRM + ECLAIRs + MXT + GWAC + GFTs) can constrain ν_c in addition to ν_m and p

- High-energy: a large ν_c (keV band) would imply a magnetic field lower than expected
- Visible: GWAC / C-GFT / Colibri observations can further constrain these parameters

Multi-wavelength study of GRB prompt emission with SVOM

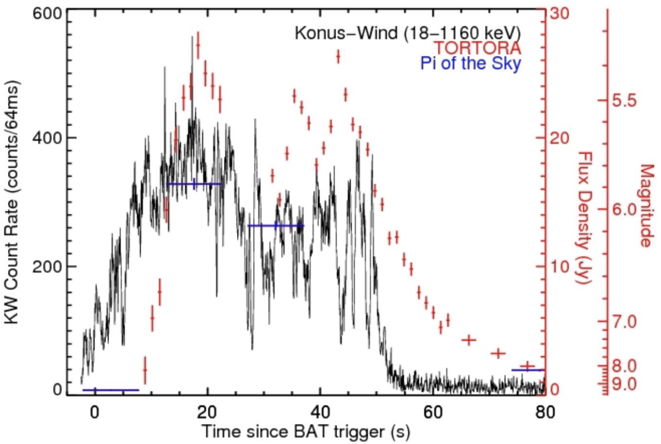
- **Prompt optical flash observed during the prompt emission (GRM + ECLAIRs + GWAC)**
  - Study of the optical variability and correlation with high energy → <u>constraints on the emission region</u>
- **Rapid broadband follow-up before the end of the prompt emission (GRM + ECLAIRs + MXT + GWAC + C-GFT/Colibri)**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

Visible (GWAC & GWAC-F60A) and X-ray (Swift/XRT) light curves of GRB 201223A.
Clear prompt-to-afterglow transition, with early visible emission consistent with the fireball scenario.



Xin+2023

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



Racusin+2008

Joint analysis with (very) high-energy instruments

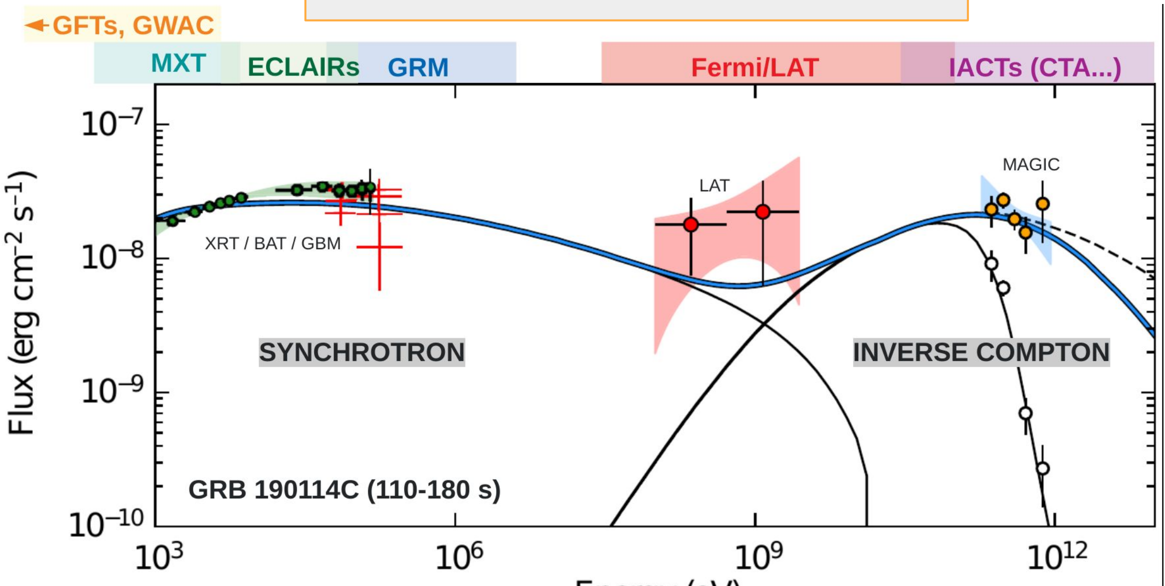
Simultaneous (visible-)keV-MeV observations are key to understand GRB GeV/TeV emissions

- For instance, prompt synchrotron emission and SSC extension to GeV/TeV range

Tools for joint spectral fits with SVOM + Fermi + MAGIC / H.E.S.S. / VERITAS / HAWC / LHAASO / CTA / etc

- XSPEC: very well supported, but limited (requires count binning in space & energy + not tailored to GRBs)
- ThreeML: "Multi-Mission Maximum Likelihood"
  - MWL/MM fits combining the native likelihoods of the detectors
  - Coherent MWL spectral analysis: one single model is fit, e.g. two correlated spectral components (SSC, etc)
  - Powerful + Frequentist or Bayesian + many GRB modules and models
- Gammapy:
  - CTA official software
  - MWL code under development
  - Not yet tailored to GRB analysis

Broad-band SED of GRB 190114C early afterglow



Adapted from Acciari+2019

谢 谢

Thank you

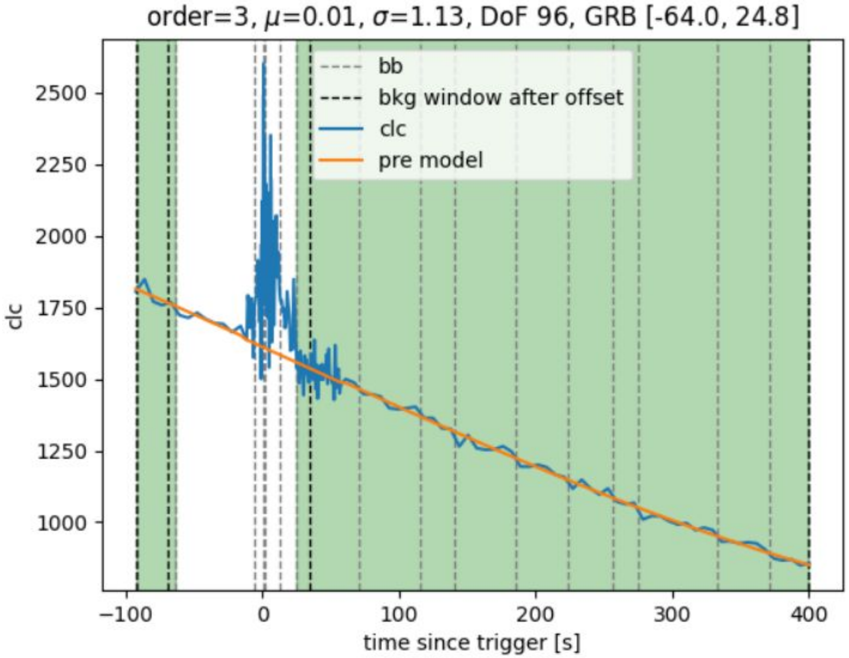
Backup

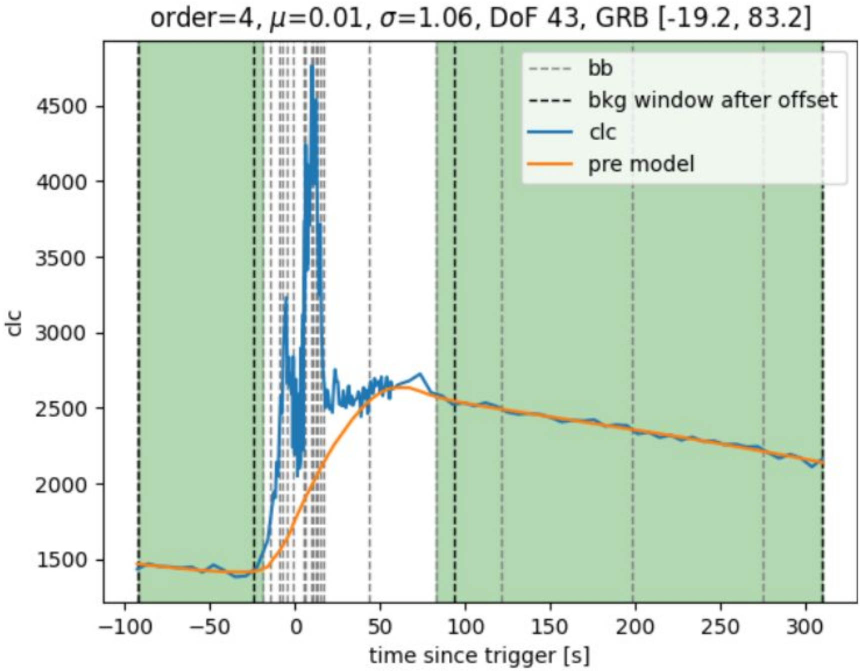
Background fit

ECLAIRs GRB (simulation without slew)

From J. Wang (IAP)

ECLAIRs GRB (simulation with slew)





Scientific Requirements for cross-calibrations

- **Mission Rationale and Requirements (SV-PRO-SP-52-JPO)**

[MRR-CAL5]

MXT and ECLAIRs cross-calibration:
(1) The flux inter-calibration between MXT and ECLAIRs in the 4-10 keV energy band shall be accurate at a level better than 10 (TBC) % at the end of the Performance and Verification phase.
(2) The spectral slope of sources described by a single power law model shall be in agreement among the two instruments to better than 10 (TBC) % over the same energy range at the end of the Performance and Verification phase.

[MRR-CAL6]

ECLAIRs and GRM cross-calibration:
(1) The flux inter-calibration between ECLAIRs and GRM in the 15-150 keV energy band shall be accurate at a level better than 20(TBC)% at the end of the Performance and Verification phase.
(2) The spectral slope of sources described by a single power law model shall be in agreement among the two instruments to better than 10 (TBC)% over the same energy range at the end of the Performance and Verification phase.

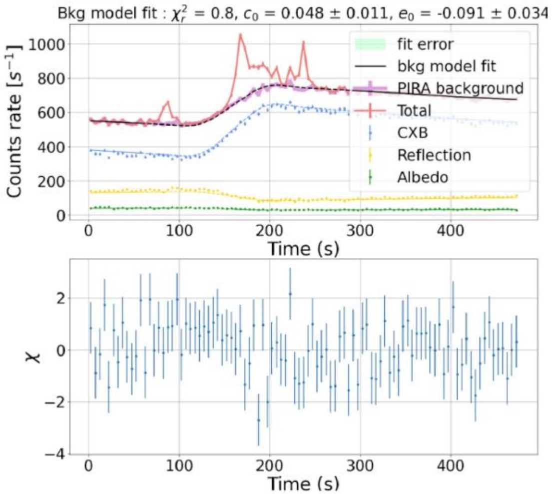
- **GRM cross-calibration plan (SV-GSGRM-YJ-201-IHEP)**

- [FR3] GRM shall measure the GRBs' peak energy in hard X and soft gamma ray band in near real-time; GRM shall be combined with ECLAIRs to estimate GRB peak energy more accurately;

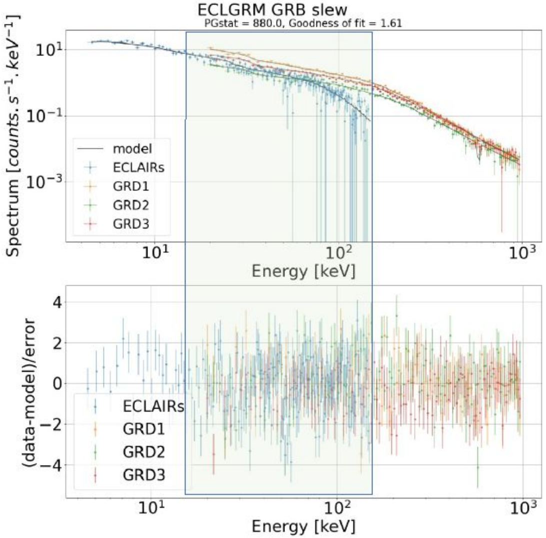
ECLAIRs / GRM cross-calibration with bright GRBs

- **Joint fits of GRB spectra with ECLAIRs / GRM / MXT (possibly also with Swift/BAT, Fermi/GBM, etc)**
  - Effective Area Corrections (EAC) as free parameters in the spectral fit → relative calibration
  - Performance: flux accuracy of ~10% (~2%) for a fluence of ~5.10^{-6} (10^{-4}) erg/cm^2
- **Method limitations**
  - GRB true spectrum is unknown → EAC strongly depend on the assumed model (circular reasoning)
  - Accurate GRM background model needed in case of slew
  - GRM response must properly account for the additional signal from scattering by Earth atmosphere

Long GRB with slew: background estimation with a physical model (CXB, reflection, albedo) in GRD2 of GRM



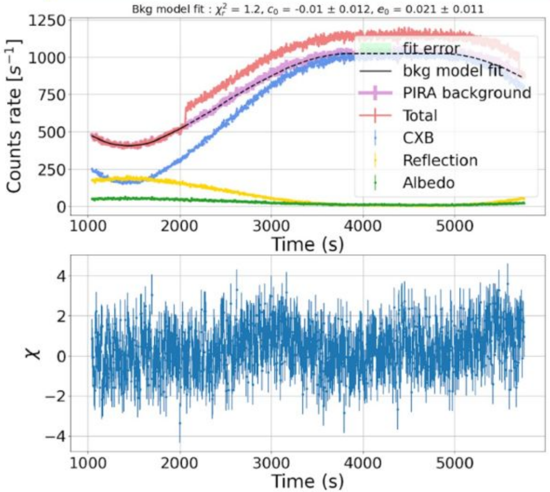
Long GRB with slew: ECLAIRs+GRM joint spectral fit



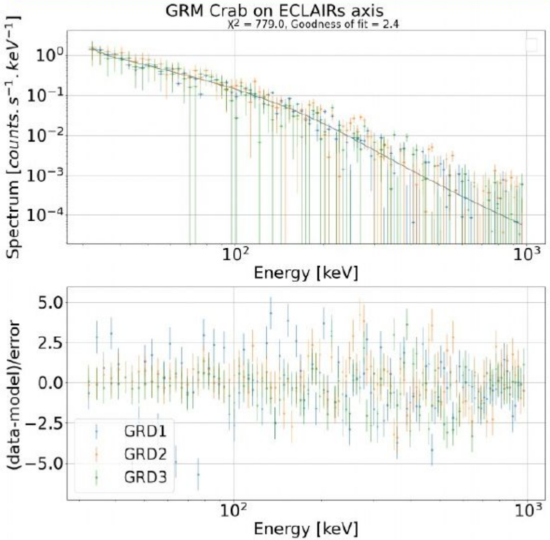
ECLAIRs-GRM cross-calibration with bright known sources

- **Compare the Crab nebula spectra measured independently by ECLAIRs and GRM**
  - Absolute calibration: no assumption on true spectrum (reference = IACHEC standards)
  - GRM is not a imager → analyse the source right before occultation / after emersion
  - Performance: few % flux accuracy can be reached with the GRM in 25 min (in 1hr with ECLAIRs)
- **Crab not observable before Fall 2024 → use Sco-X1, Cyg-X1 (high state) during commissioning**
  - Relative ECLAIRs / GRM calibration, possibly simultaneous observations by Swift or Integral
- **Method limitations**
  - Accurate GRM background model (~5-10%)

Crab nebula: background estimation with a physical model (CXB, reflection, albedo) in GRD1 of GRM



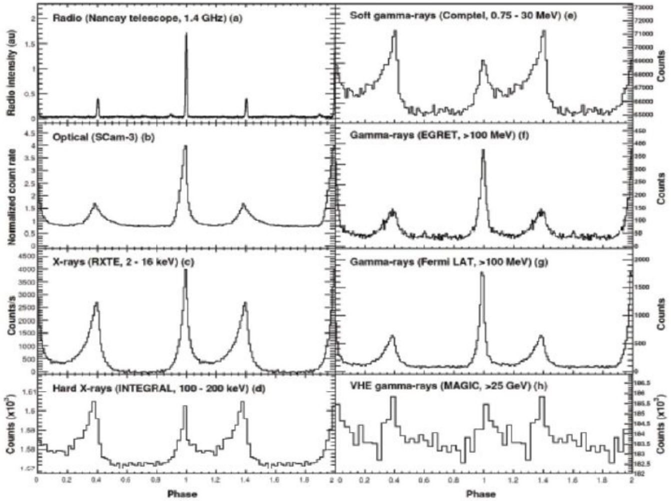
Crab nebula (25 min exposure): GRM spectral fit (20 keV – 1 MeV)



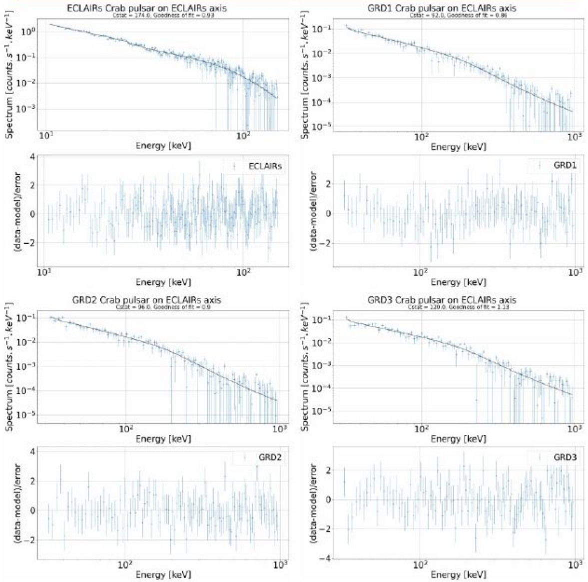
ECLAIRs-GRM cross-calibration with pulsars

- **Compare the Crab pulsar spectrum measured independently by ECLAIRs and GRM**
  - “Absolute” calibration: weak assumption on the source true spectrum
  - Phasogram is flat between pulses → accurate background estimation
  - Performance: few % (~1%) flux accuracy can be reached in ~10 (~100) orbits
- **Method limitation**
  - Pulsed emission is only a few % of the nebula emission → long exposure needed

Crab pulsar phasogram in different energy bands



Crab pulsar (10 orbit exposure): spectral fits with ECLAIRs and GRDs

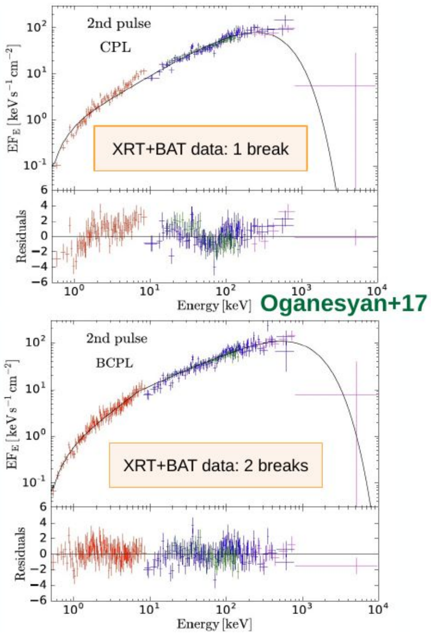


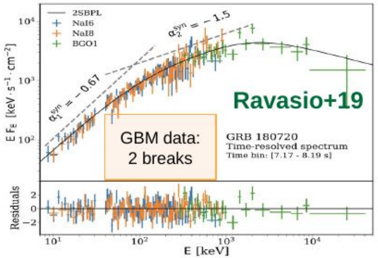
MXT-ECLAIRs cross-calibration with bright known sources

- **Motivation: there is a significant overlap between MXT and ECLAIRs energy ranges (4-10 keV). Some sources can be observed simultaneously by both instruments, in particular**
  - CP: very long GRBs and bright happening not too far from ECLAIRs axis, can be observed after the satellite slew by both telescopes providing unique broad band spectra from 0.1 to 150 keV (even more if GRM can contribute); 1 vs 2 break synchrotron models can be tested, potentially solving the alpha index >-2/3 ("line-of-death") problem
  - GP: would benefit from well calibrated broad-band spectra

- **Compare the Crab nebula spectra measured independently by ECLAIRs and MXT**
  - Absolute calibration: no assumption on true spectrum (reference = IACHEC standards).
  - Performance: Few % accuracy can be reached by MXT in one orbit. More exposure needed for ECLAIRs.
  - Some GRM/ECLAIRs Crab time can be used for this task, if on-axis for ECLAIRs

- **Crab not observable before Fall 2024 → use Cyg-X1 (TBC) during commissioning**
  - Relative ECLAIRs / MXT calibration, possibly simultaneous observations by Swift or INTEGRAL





7

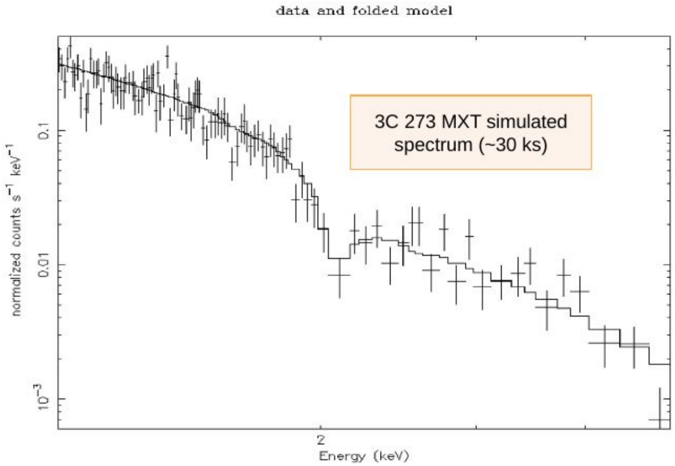
MXT-ECLAIRs cross-calibration with weak sources

- **The 4-10 keV range can be characterized also using AGNs, like 3C273, Mrk 421, whose spectrum is well known and relatively stable**
  - MXT will obtain a good precision within 30 ks
  - Ms of observation time is probably required by ECLAIRs, but those sources are compatible with the B1 law, and so will be observed by ECLAIRs for a long period over the year

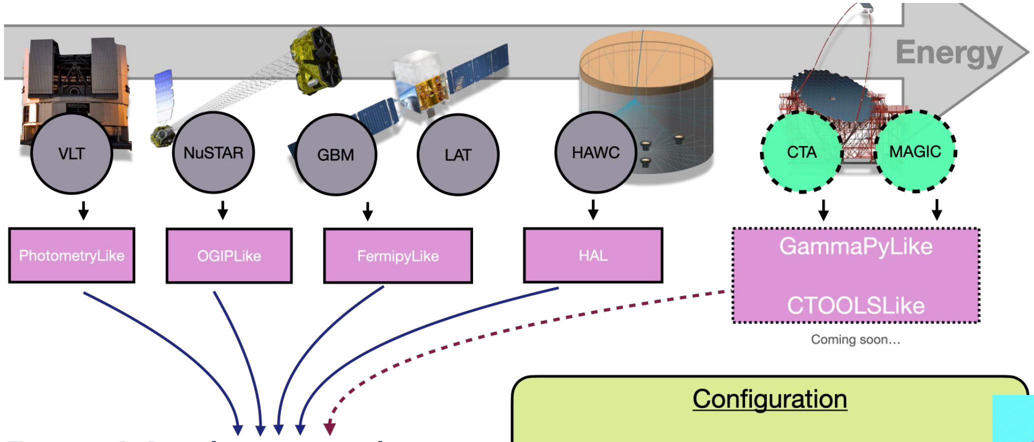
- **Method limitations**
  - Long exposure needed
  - Intrinsic AGN variability

Example of 3C 273 MXT simulation:

- 3C 273 is only 13° off the B1 law
- Simulated input spectrum: XMM EPIC/pn (Madsen+17)
- 30 ks observation, the flux can be measured with a +/- 7% accuracy
- Photon index 90% c.l. range 1.52 - 1.77; input 1.69; 4% accuracy
- With a ~200 ks observation uncertainties shrink to about 2% in photon index and 1% in flux.



How 3ML works

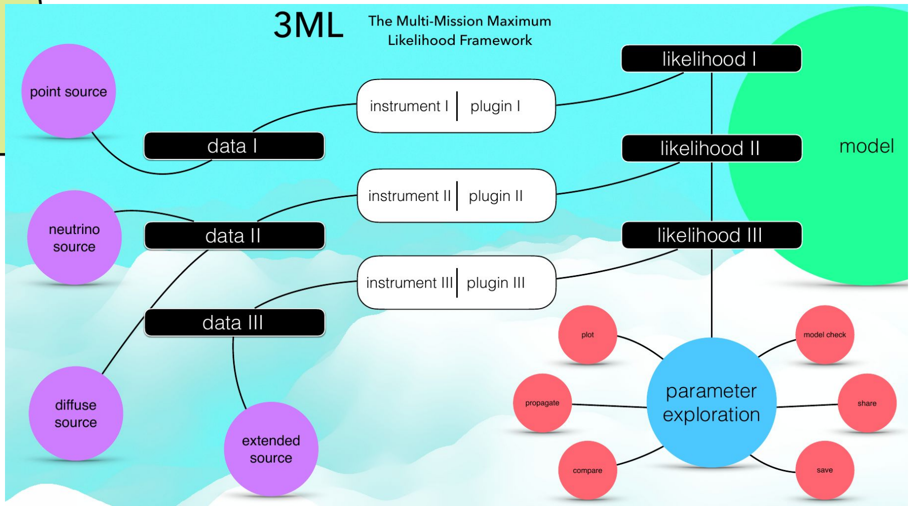


DataList(. . .)

<u>Configuration</u>

(Fermipy, HAL, gammapy, CTOOLS)

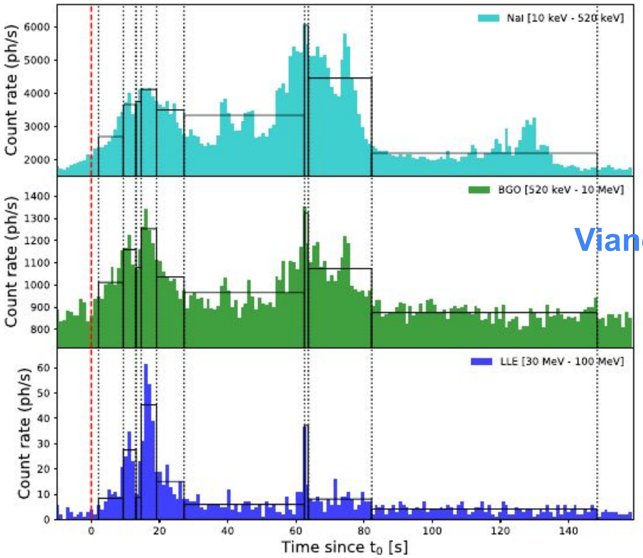
Interaction with expert-built software



Burgess, J.M. 2022, INTEGRAL Conference

Example of joint spectral analysis with 3ML

Fermi GRB100724B: multi-detector LC



Fermi GRB100724B: time-resolved spectral analysis with phenomenological and physical models

Vianello et al. 2018, ApJ 864, 163

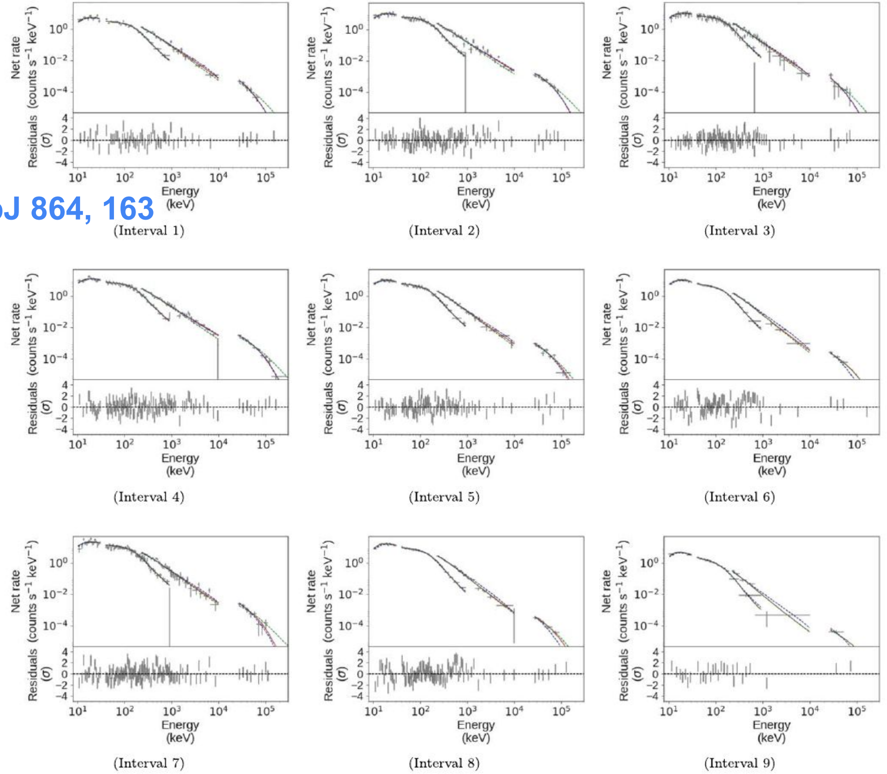


Figure 8. Counts spectra for GRB 100724B for the NaI, BGO, and LAT detectors (gray points). The lines correspond to the models $f_{\rm BHec}$ (continue line), $f_{\rm GT}$ (blue dashed line), and $f_{\rm BG}$ (green dashed line), convolved with the response of the instruments. The residuals are relative to the $f_{\rm BHec}$ model.

Model	Description
$f_{\rm Band}$	Band function
$f_{\rm BB}$	Band function plus blackbody
$f_{\rm BHec}$	Band function with high-energy exponential cutoff
$f_{\rm Bbkpo}$	Band function with broken power-law spectrum above the peak
$f_{\rm Bgr}$	Band function with gradual break in the power-law spectrum above the peak
$f_{\rm BG}$	Band function with high-energy spectral break due to $\gamma\gamma$ pair opacity
$f_{\rm GT}$	Spectrum from delayed pair breakdown model in a strongly magnetized jet
$f_{\rm th}$	Quasi-thermal spectrum described by a power law plus a Wein peak