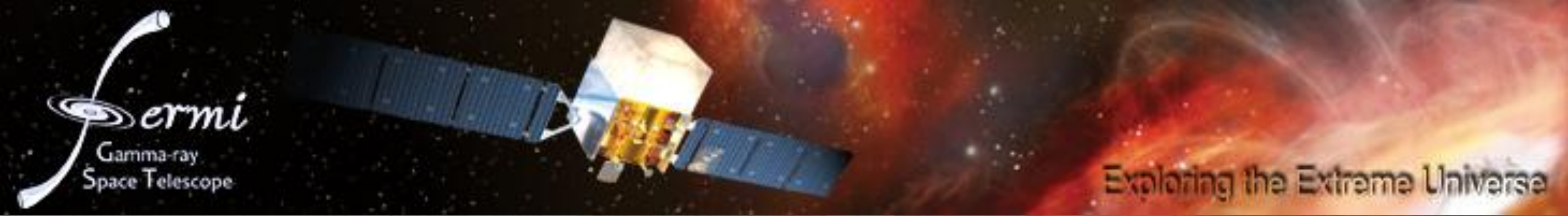
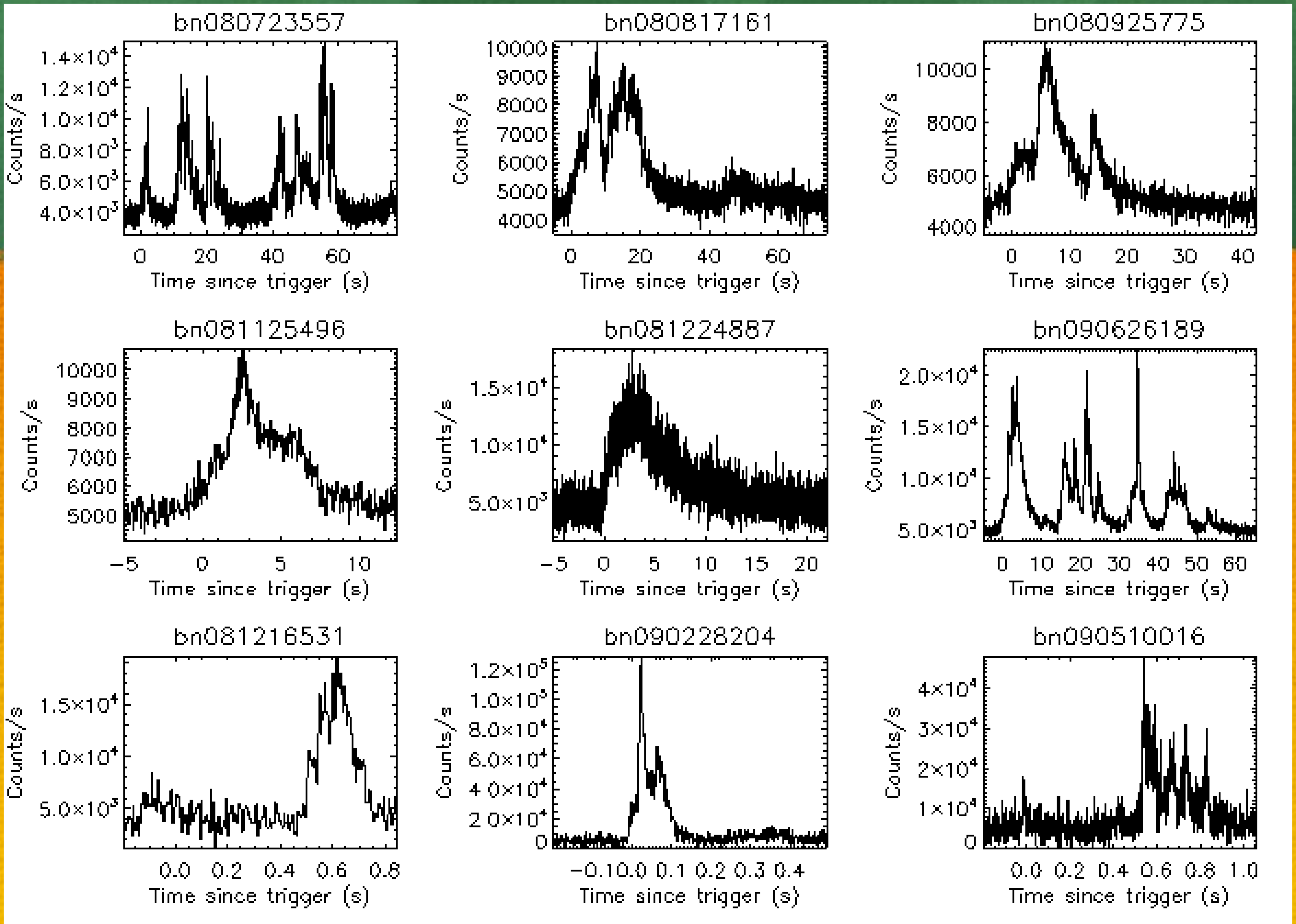


What more do we know about

Gamma-ray Bursts in the Fermi Era

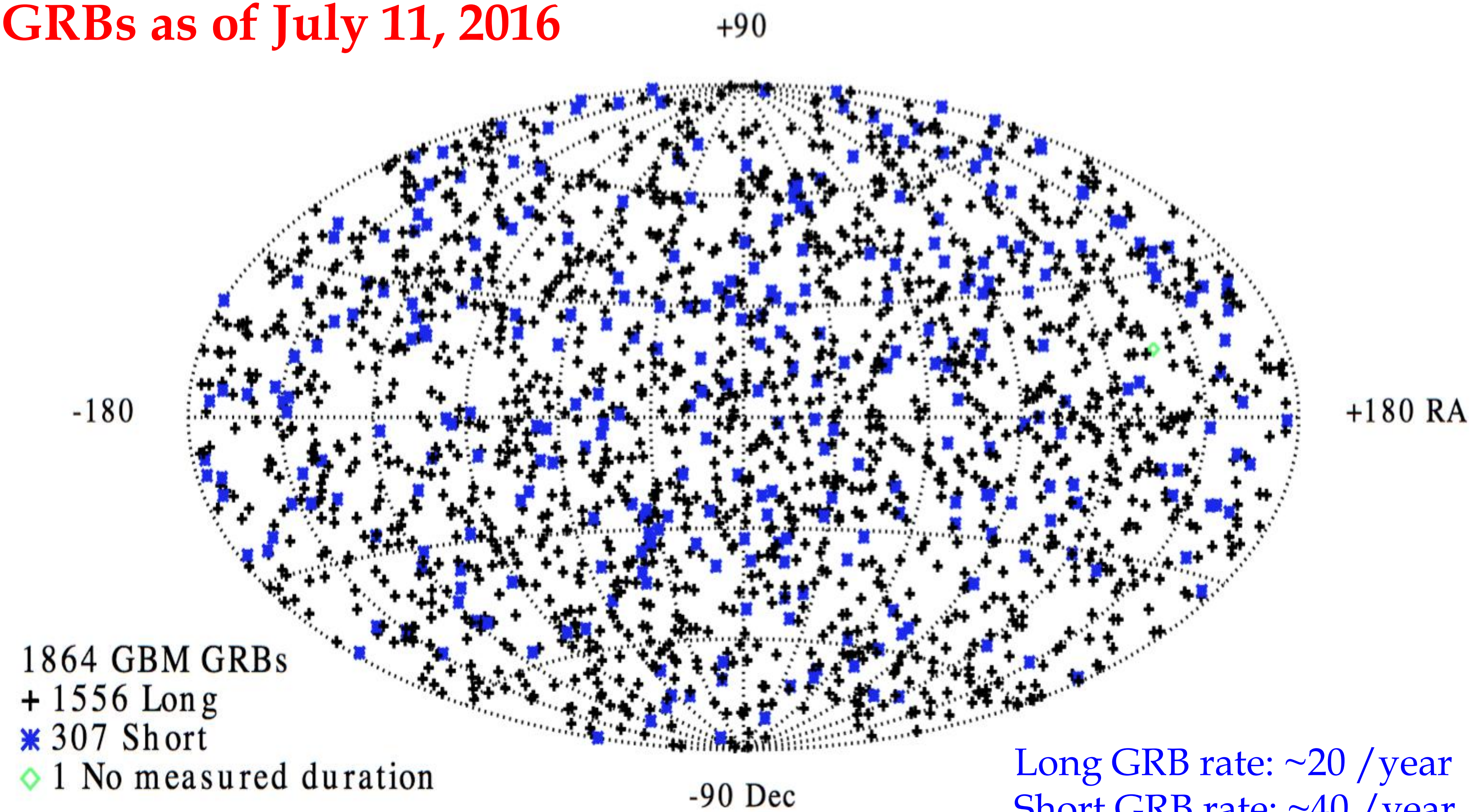
Narayana.Bhat@nasa.gov
University of Alabama in Huntsville
USA


bn080723557
bn080817161
bn080925775
bn081125496
bn081224887
bn090626189
bn081216531
bn090228204
bn090510016
Counts/s
Time since trigger (s)

- GRBs were discovered serendipitously by the Vela Satellites in the late 1960s, and the data were reported several years later.

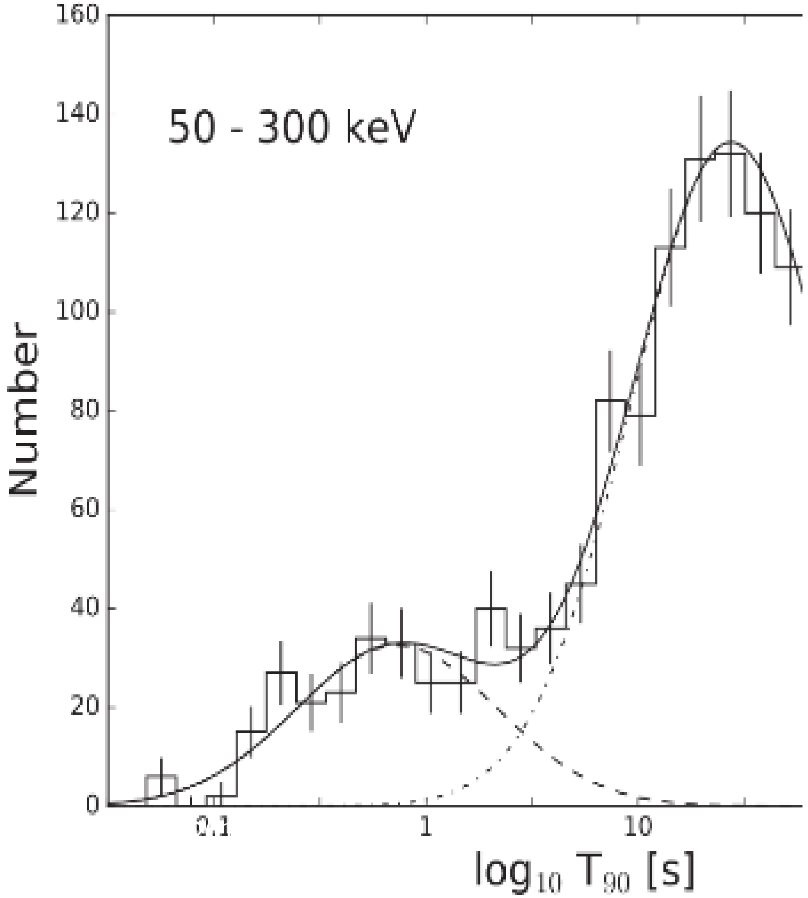
- The Compton Gamma-ray Observatory (CGRO) was launched in 1991, with the Burst and Transient Experiment (BATSE) on board; BATSE provided evidence for an isotropic spatial distribution of GRBs, giving significant support to a cosmological origin interpretation

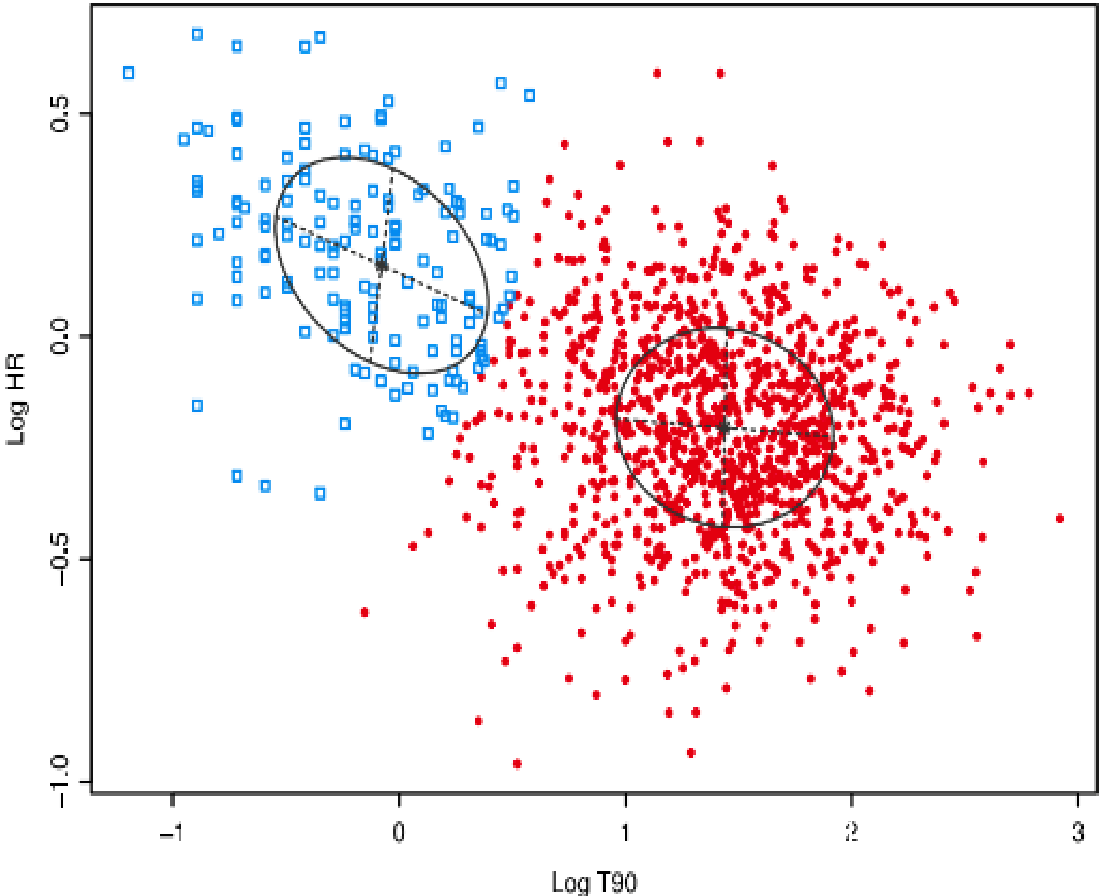
GRBs as of July 11, 2016



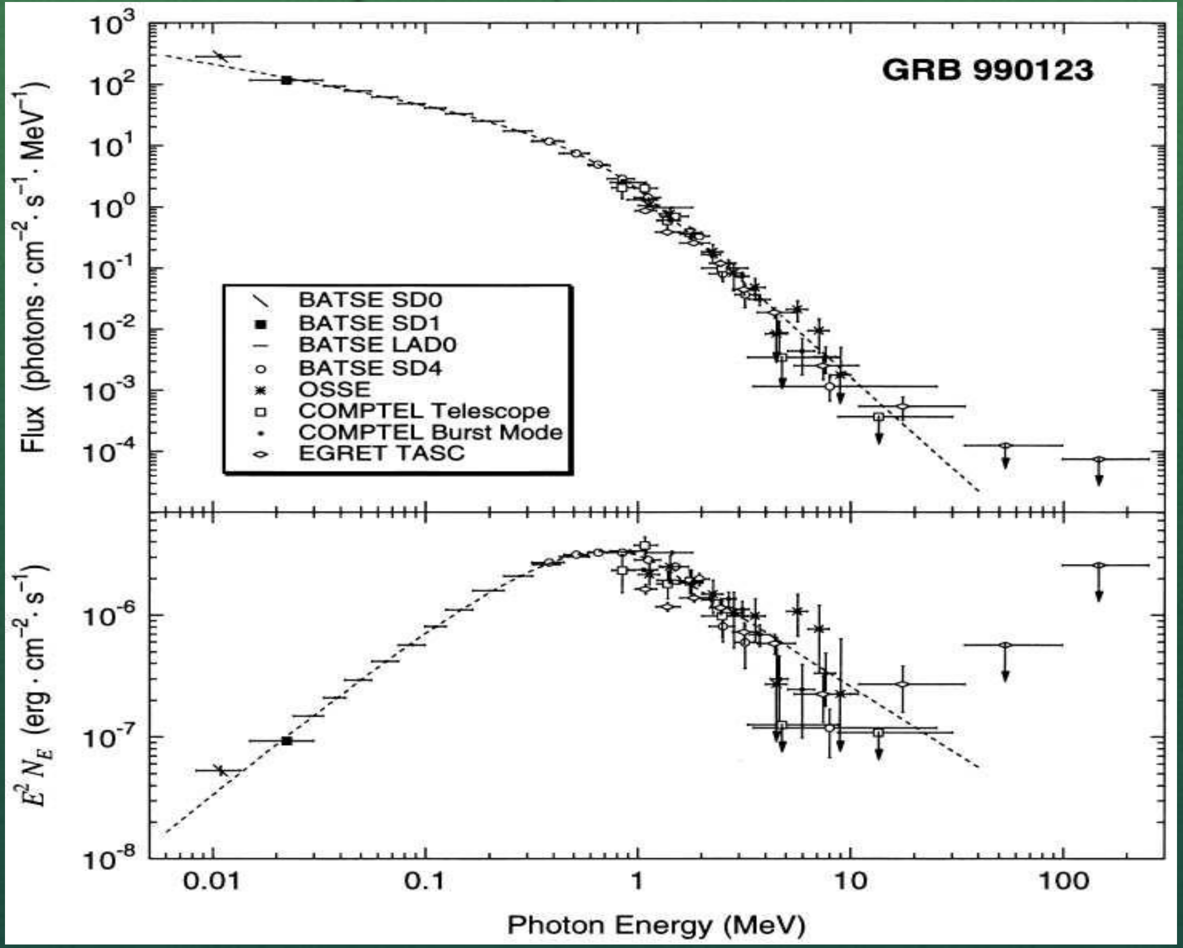
Long GRB rate: ~20 / year
Short GRB rate: ~40 / year

- Two categories of GRBs, “long” (t >~2 s) and “short”, (t <~ 2 s) were identified

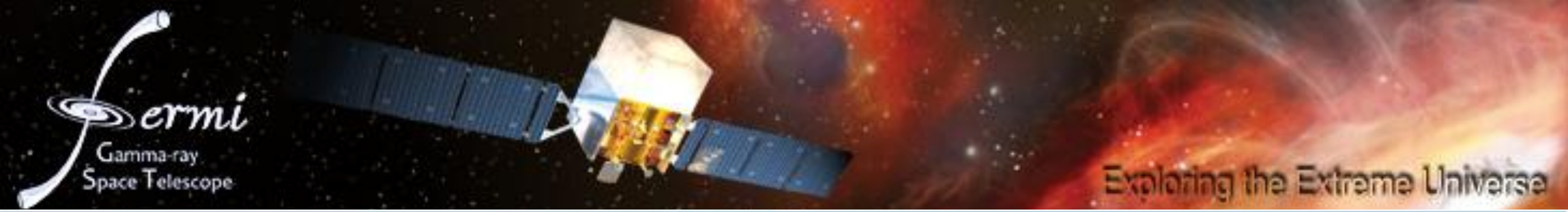


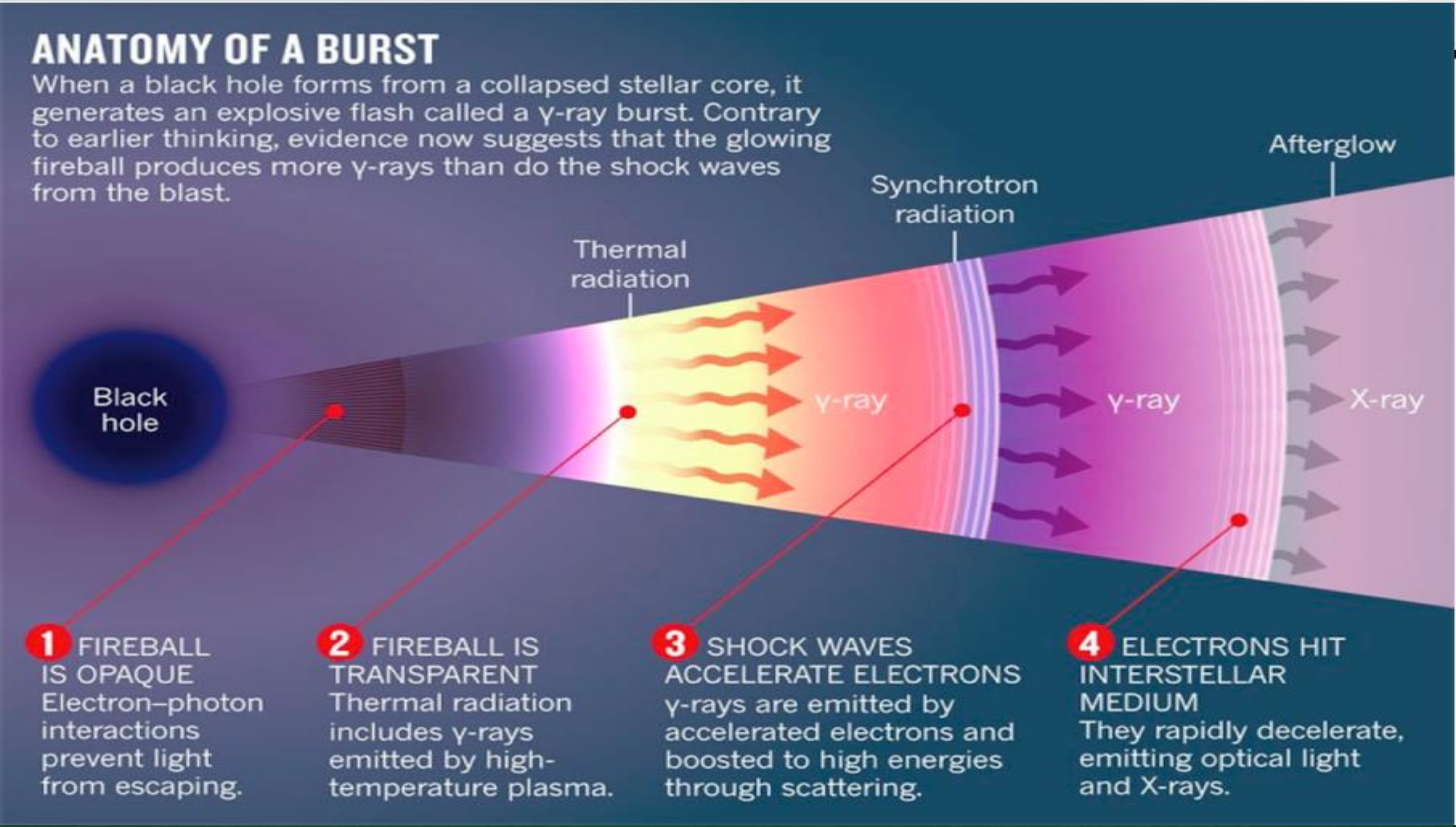


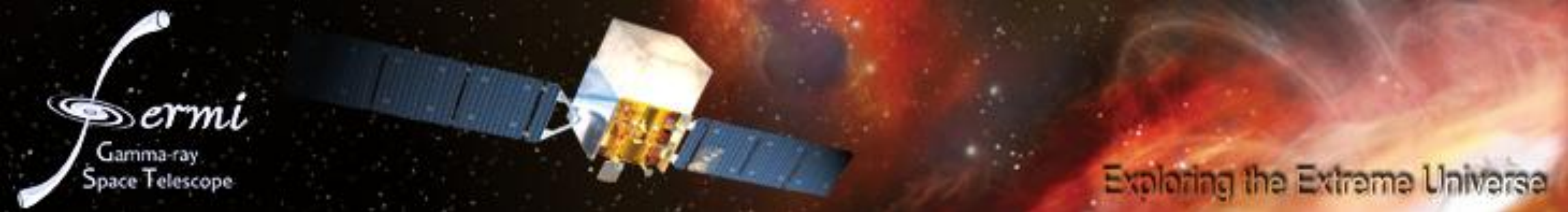
• Systematic analyses of GRB spectral data indicate that a so-called "GRB function" (or "Band function") fits reasonably well most of the GRB spectra (for both classes of bursts)



- In 1997, the Italian-Dutch satellite Beppo-SAX pinpointed the first GRB low energy afterglow (for GRB 970228) in the X-ray band, facilitating optical and radio detections;
- The first measurements of the GRB redshifts were obtained (for GRB 97050826 and GRB 97121427, giving a solid proof that GRBs are at cosmological distances;
- A likely GRB-supernova association (GRB 980425 vs. SN 1998bw) was discovered;
- A bright and prompt optical flash and a radio flare were discovered to accompany the energetic burst GRB 990123;
- An achromatic steepening break in the afterglow light curves was found in several bursts, hinting that at least some GRB fireballs are likely to be collimated
- X-ray spectral features with moderate significance were discovered in several GRB X-ray afterglows


Fermi
Gamma-ray
Space Telescope
Exploring the Extreme Universe


ANATOMY OF A BURST
When a black hole forms from a collapsed stellar core, it generates an explosive flash called a γ-ray burst. Contrary to earlier thinking, evidence now suggests that the glowing fireball produces more γ-rays than do the shock waves from the blast.
Afterglow
Synchrotron radiation
Thermal radiation
Black hole
γ-ray
γ-ray
X-ray
1 FIREBALL IS OPAQUE
Electron–photon interactions prevent light from escaping.
2 FIREBALL IS TRANSPARENT
Thermal radiation includes γ-rays emitted by high-temperature plasma.
3 SHOCK WAVES ACCELERATE ELECTRONS
γ-rays are emitted by accelerated electrons and boosted to high energies through scattering.
4 ELECTRONS HIT INTERSTELLAR MEDIUM
They rapidly decelerate, emitting optical light and X-rays.



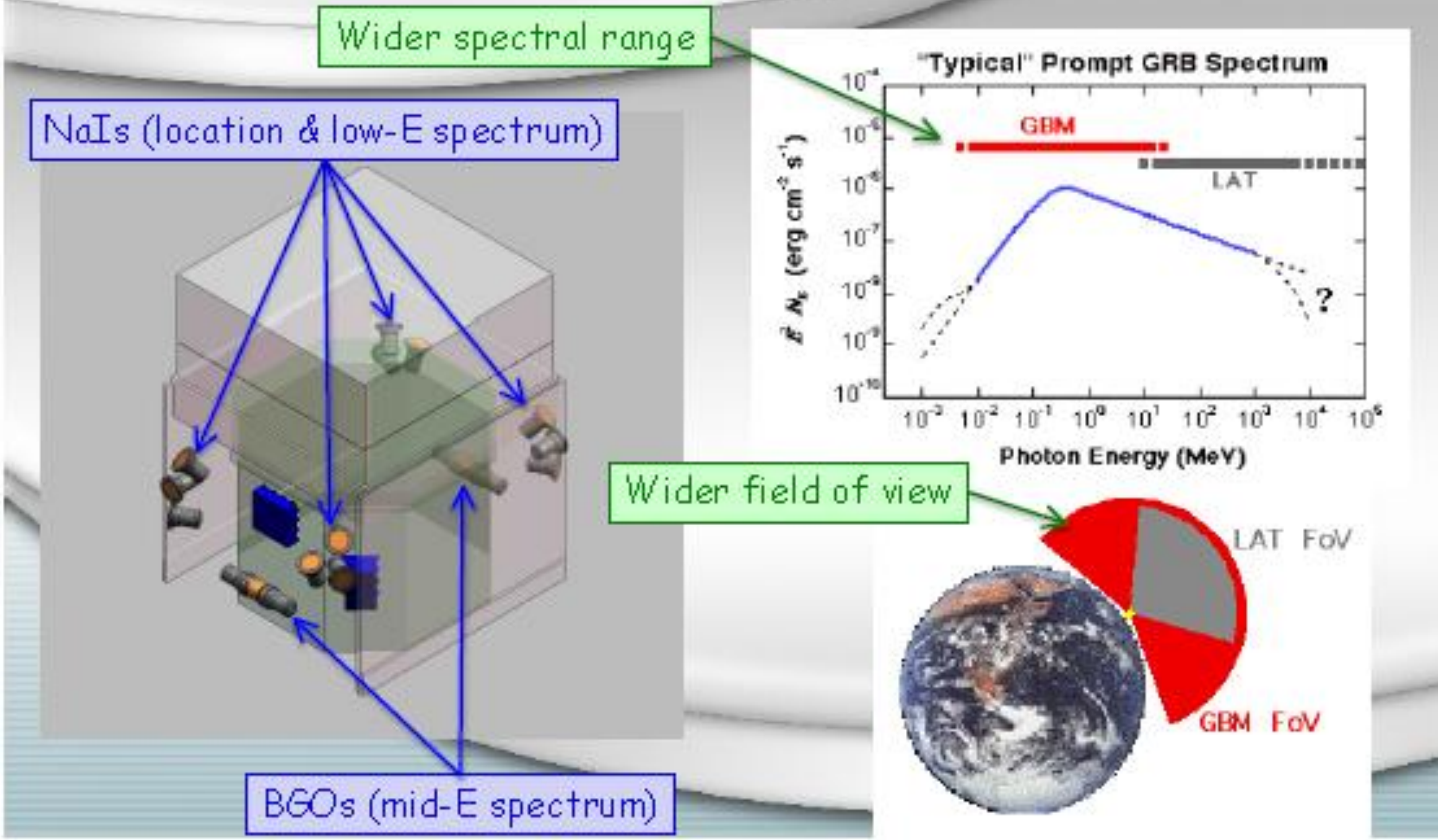
Large Area Telescope (LAT)
20 MeV - >300 GeV

Gamma-ray Burst Monitor (GBM)
NaI and BGO Detectors
8 keV - 40 MeV

KEY FEATURES

- **Huge field of view**
  - LAT: 20% of the sky at any instant; in sky survey mode, expose all parts of sky for ~30 minutes every 3 hours. GBM: whole unocculted sky at any time.
- Huge energy range, including largely unexplored band 10 GeV - 100 GeV. **Total of >7 energy decades!**
- Large leap in all key capabilities. Great discovery potential.

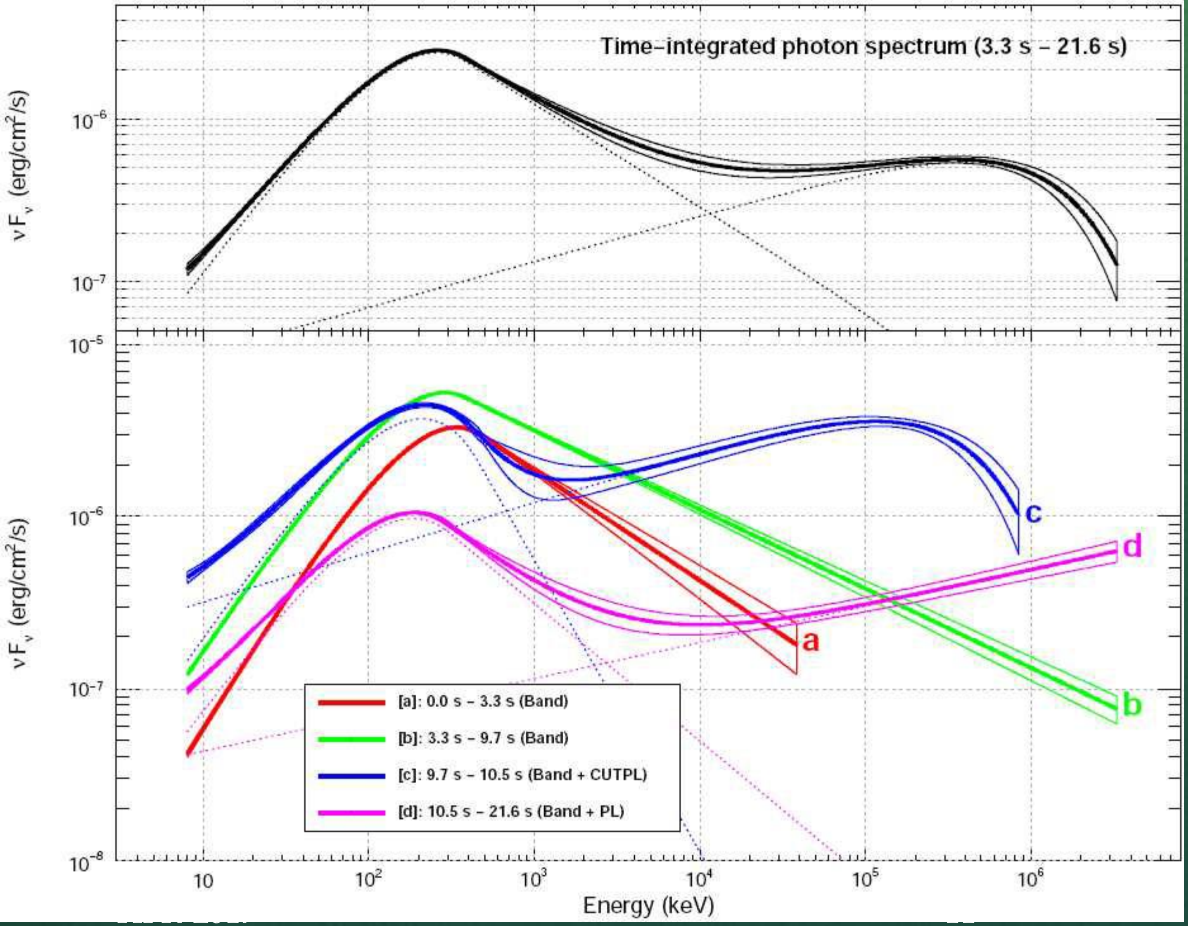
Why GBM?


Wider spectral range
NaIs (location & low-E spectrum)
BGOs (mid-E spectrum)
"Typical" Prompt GRB Spectrum
GBM
LAT
?
Photon Energy (MeV)
Wider field of view
LAT FoV
GBM FoV

GRB Spectral Analysis

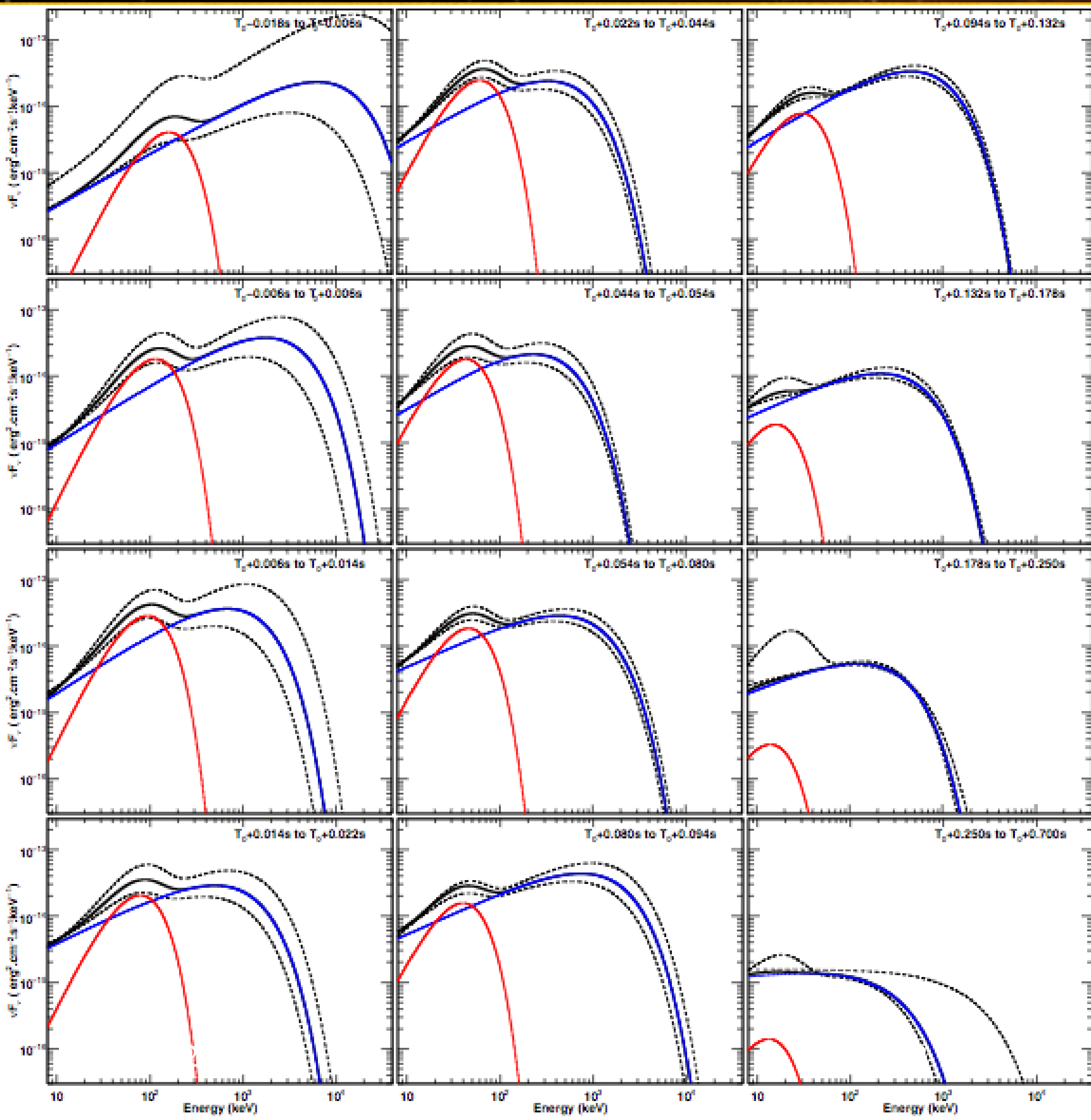
Exploring the Extreme Universe

- Systematic analyses of GRB spectral data indicate that a so-called "GRB function" (or "Band function") fits reasonably well most of the GRB spectra (for both classes of bursts)



Top panel: νF_ν time integrated spectrum of GRB 090926A. As for GRB090902B, an additional power law is required together with the traditional Band function. However, in this case, a break can be measured in the additional power law around tens of MeV. Bottom panel: Time resolved νF_ν spectra of GRB 090926A. Initially, the prompt emission spectrum is well fit with a single Band function.

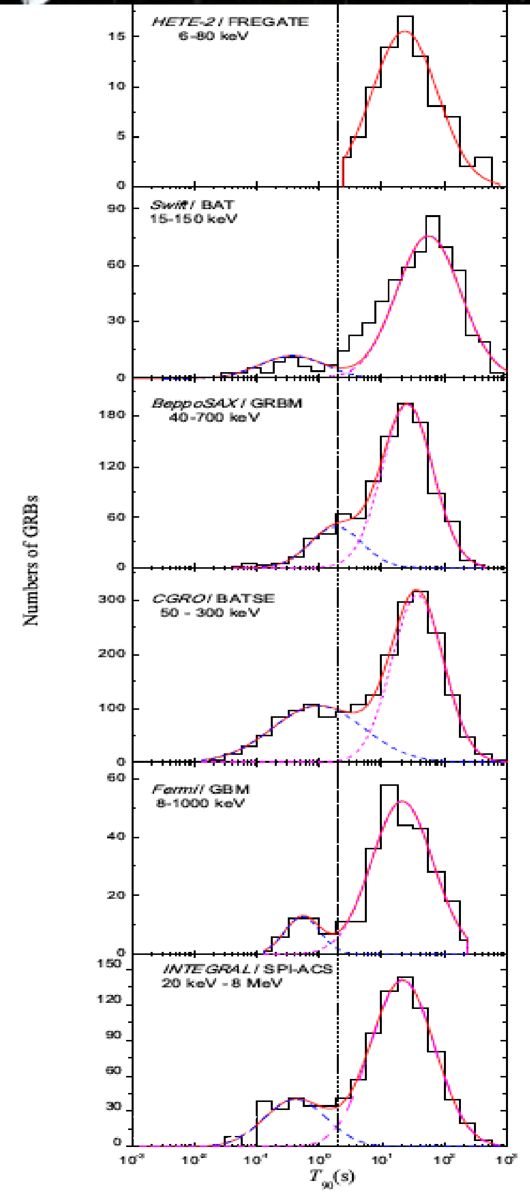
After few second, the additional power law kicks off.



Fine time-resolved vFv spectra using C+BB (equivalent to B+BB). The blue lines correspond to the Band function, the red ones to the BB component, and the black lines are the sum of the two components. The solid black lines correspond to the model obtained with the best parameters from the fits, and the thin black lines correspond to the 1σ uncertainty on the best fits.

GRB Durations

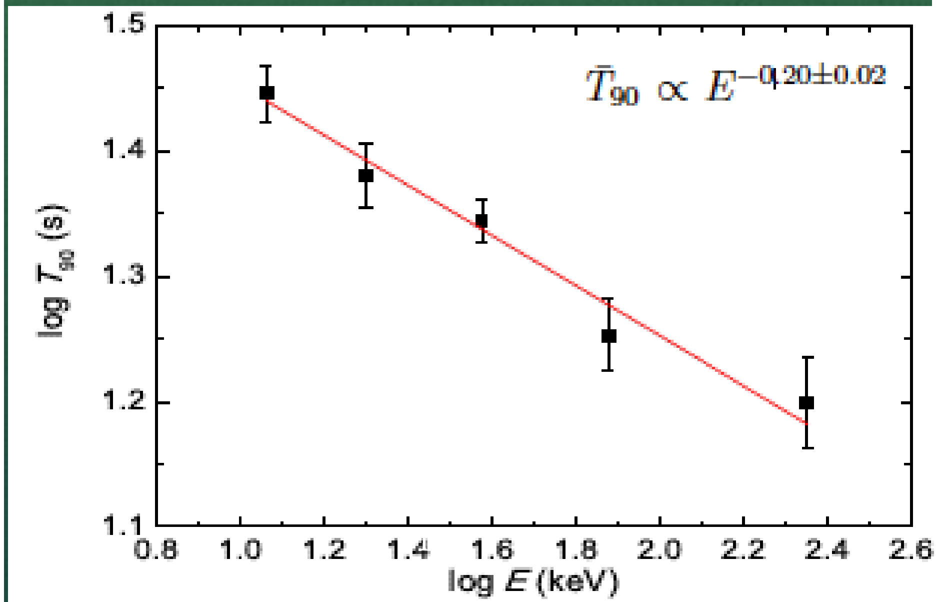
Fermi Gamma-ray Space Telescope — Exploring the Extreme Universe

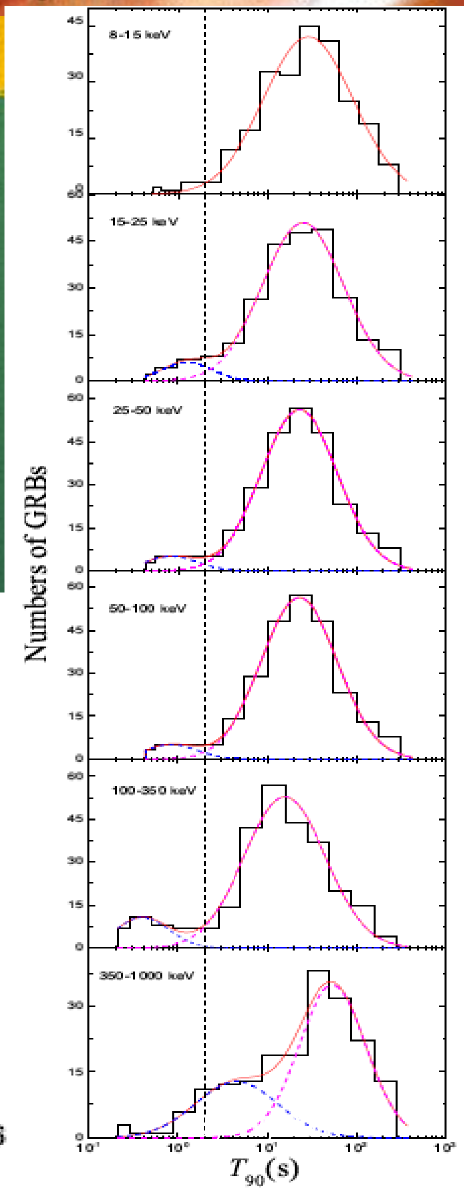


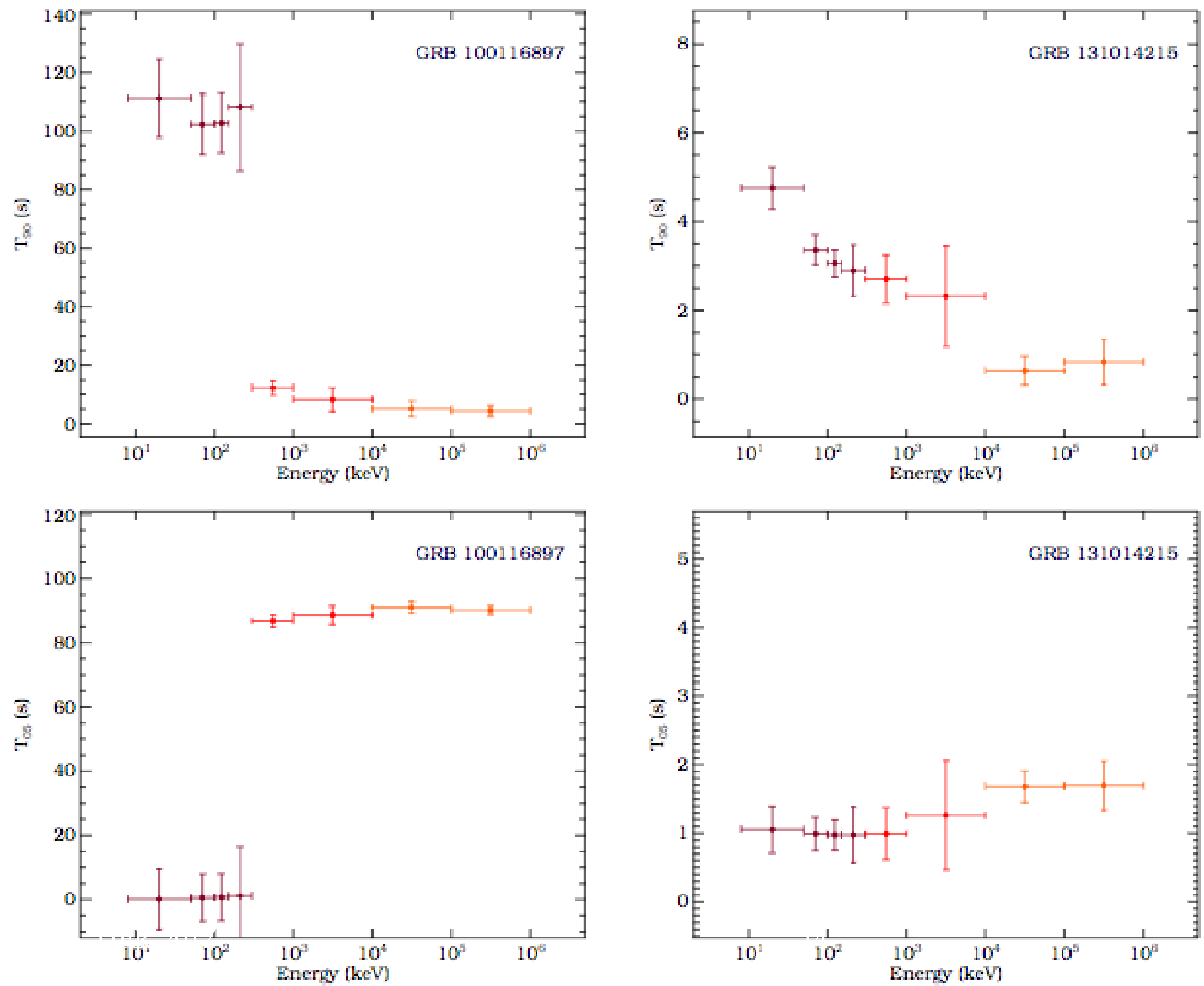
← Comparison of the T90 distributions observed with different instruments.

T_{90} distributions in different energy bands. The dotted line corresponds to T_{90} = 2 seconds.→

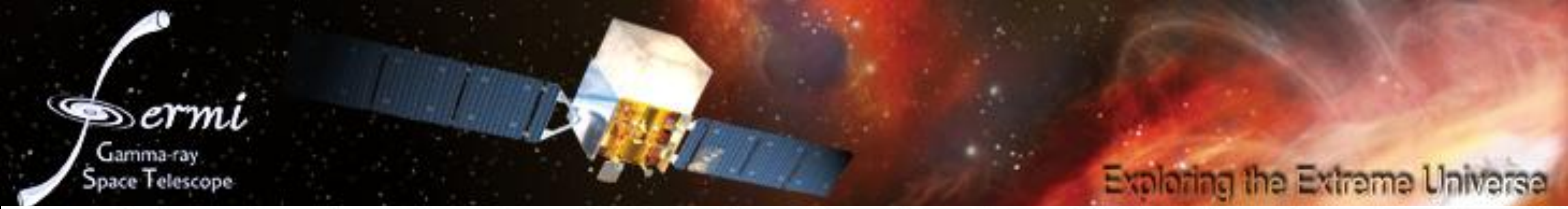
Energy dependence of T90 for the LGBRs in our sample. The solid line is the best fit to the data. ↓

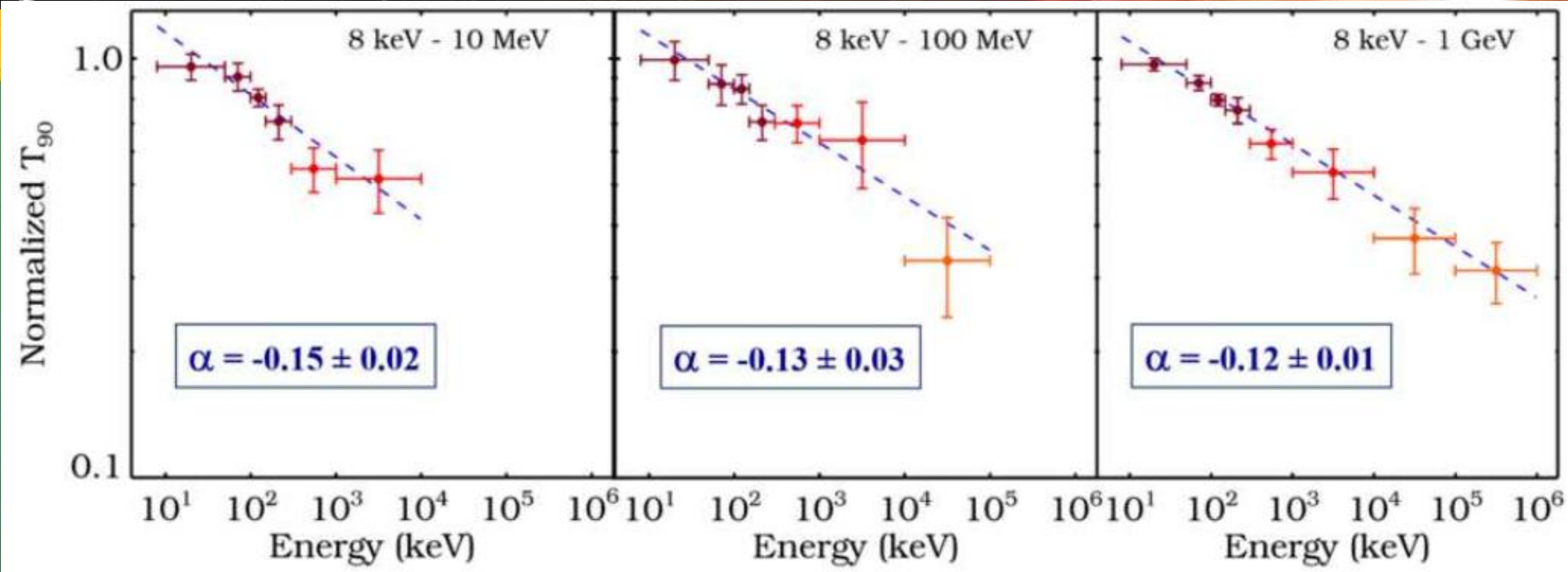






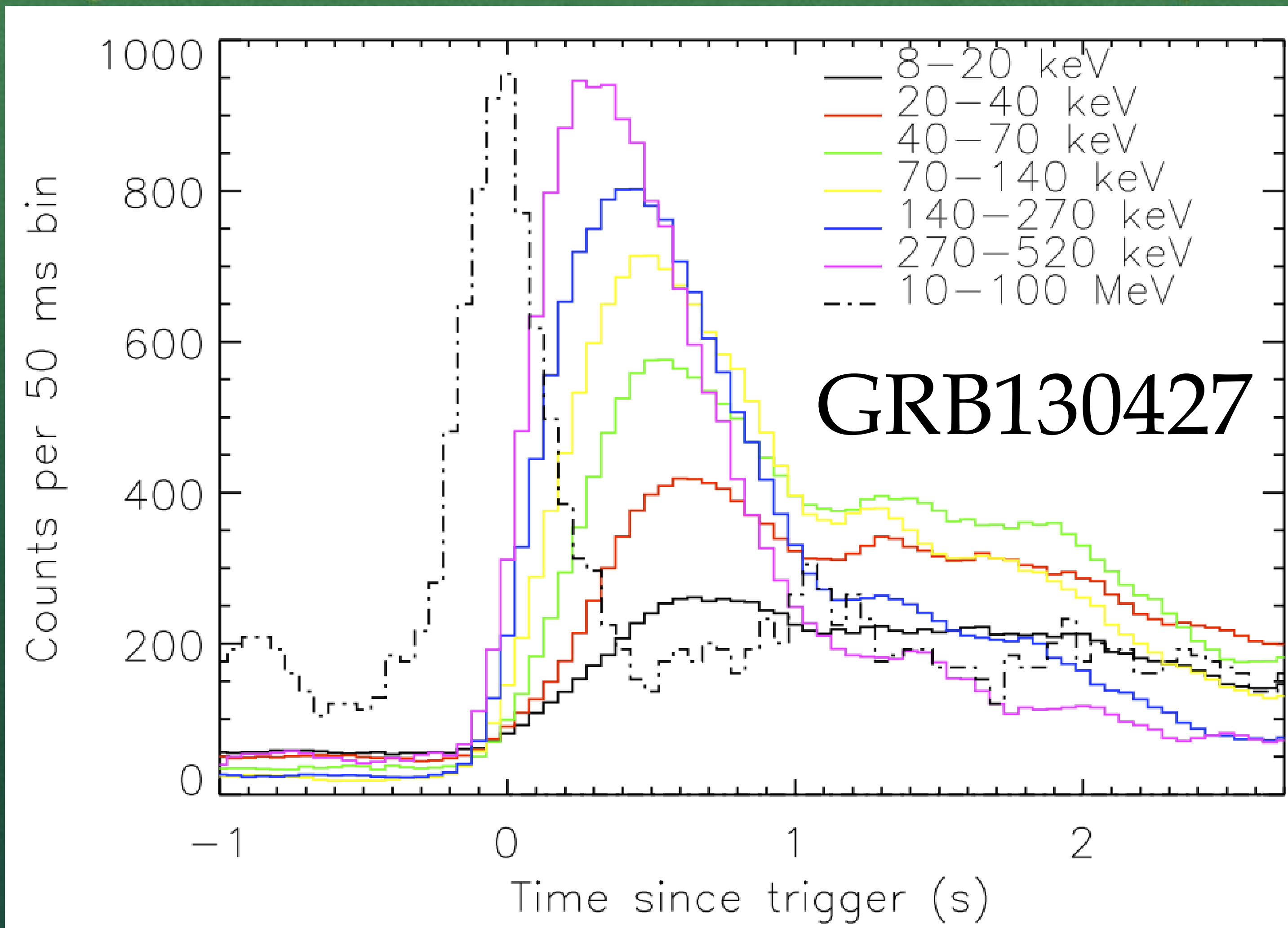
Duration (T_{90}) –Energy relation (top panels) and T_{05}–energy relation (bottom panels) calculated for GRB 100116A (left) and GRB 131010A (right). In the case of GRB 100116A, the duration drops from T90~110 s to just few seconds, while GRB131014A's duration smoothly decreases from one energy band to the next. This effect is visible also in the T05 vs. Energy plots, where the delayed start of the higher–energy emission in GRB 131014A is clearly visible.



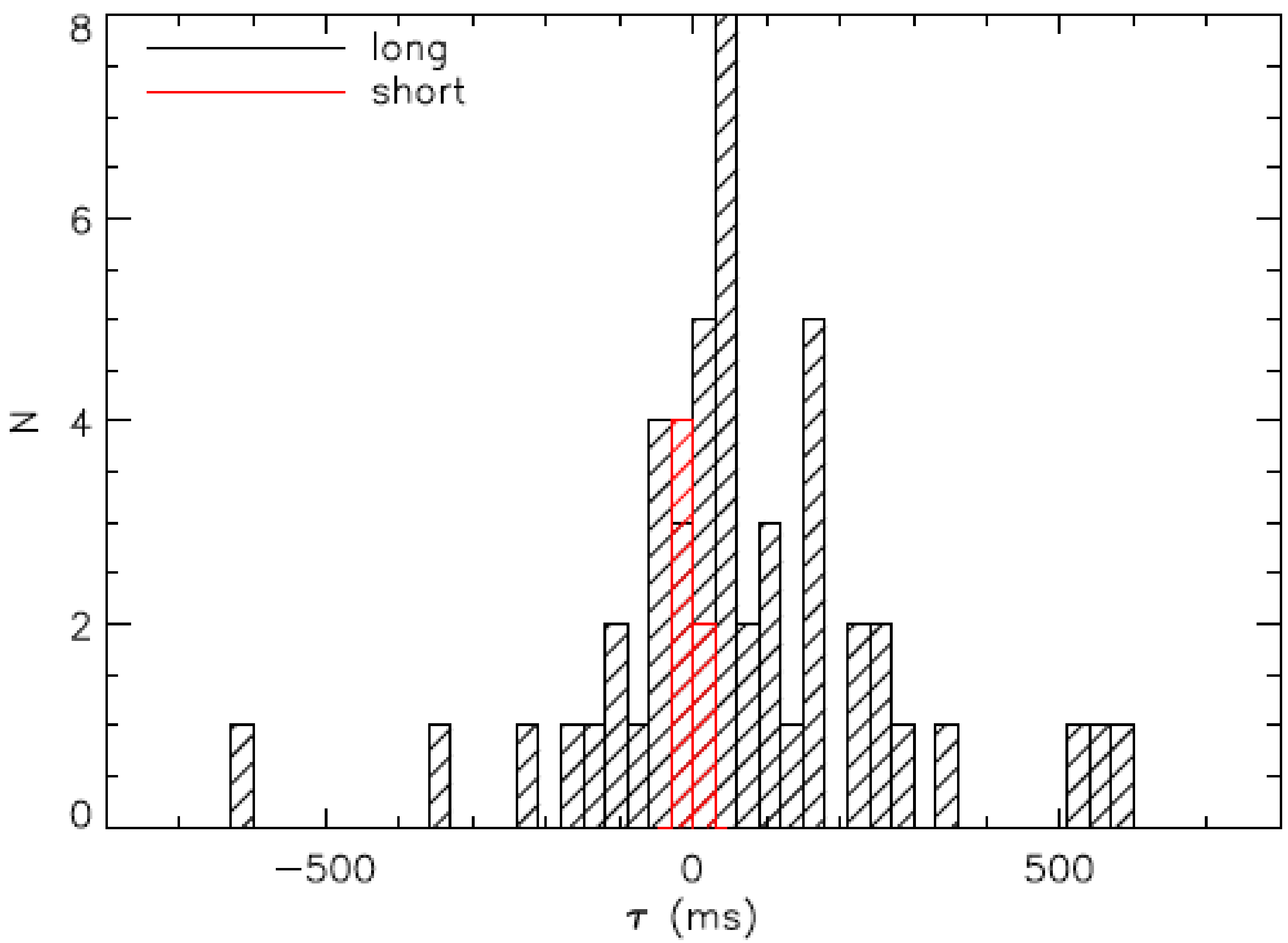


Normalized Duration T_{90}–Energy relation calculated for the 27 bright bursts of our subsample. 7 GRBs in our sub-sample are detected only up to 10 MeV, so no LLE duration could be computed (left panel). Other 7 GRBs are detected in LLE but only up to 100 MeV (middle panel), while 13 GRBs are detected all the way up to 1 GeV (right panel).

GRB Spectral Lags

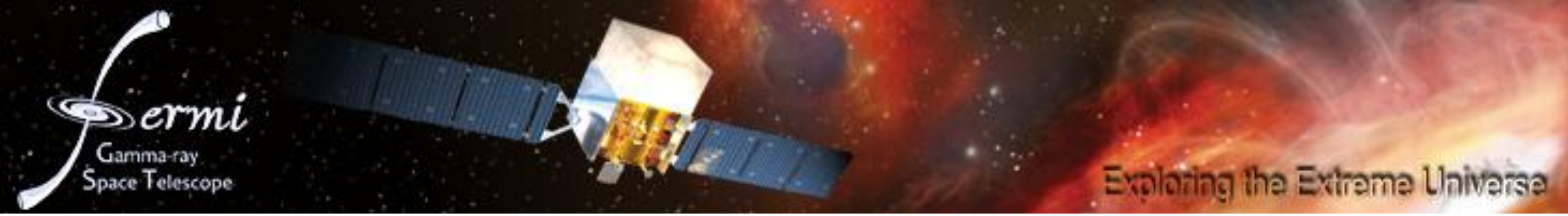


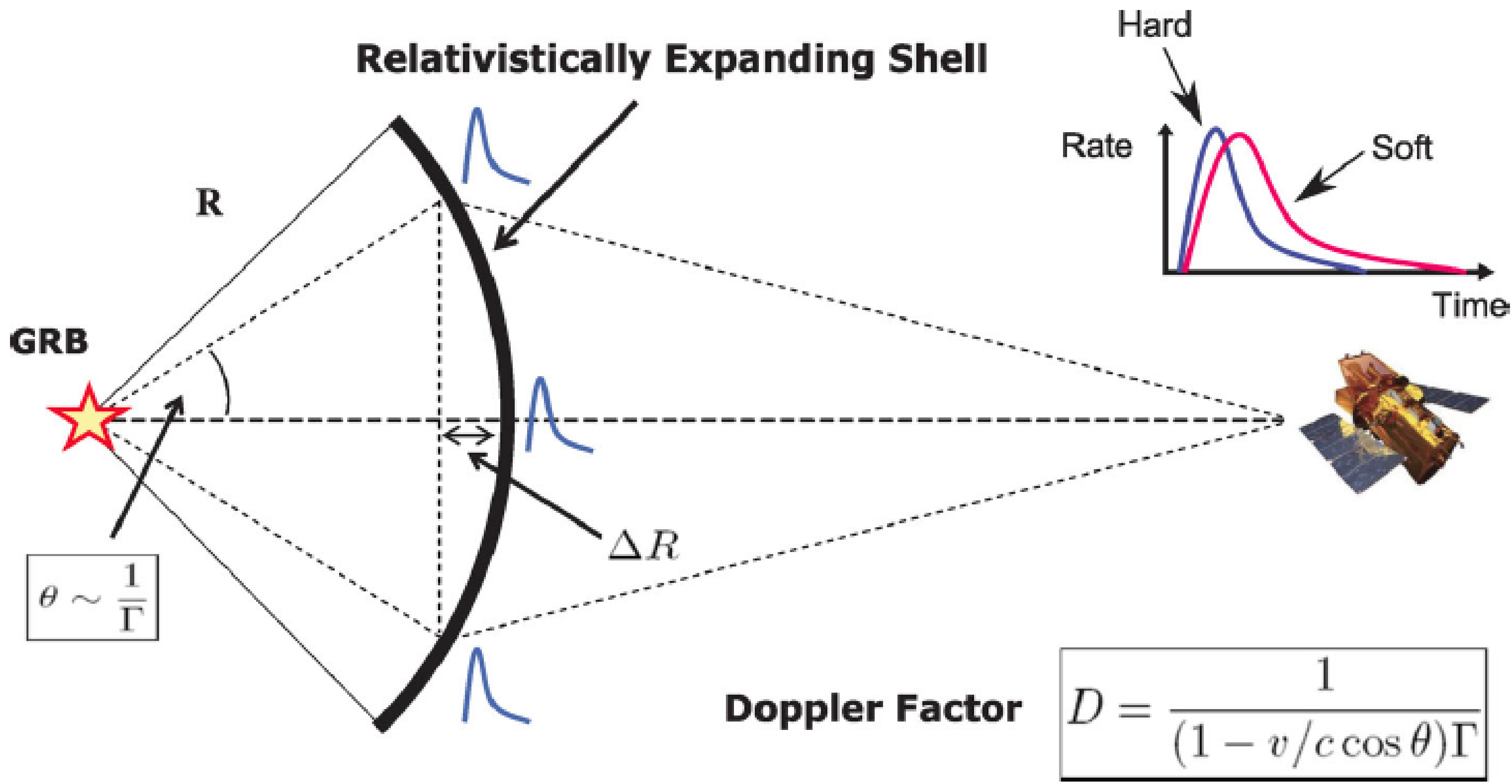
The lags were estimated between 100-150 keV and 200-250 keV rest frame energy bands.



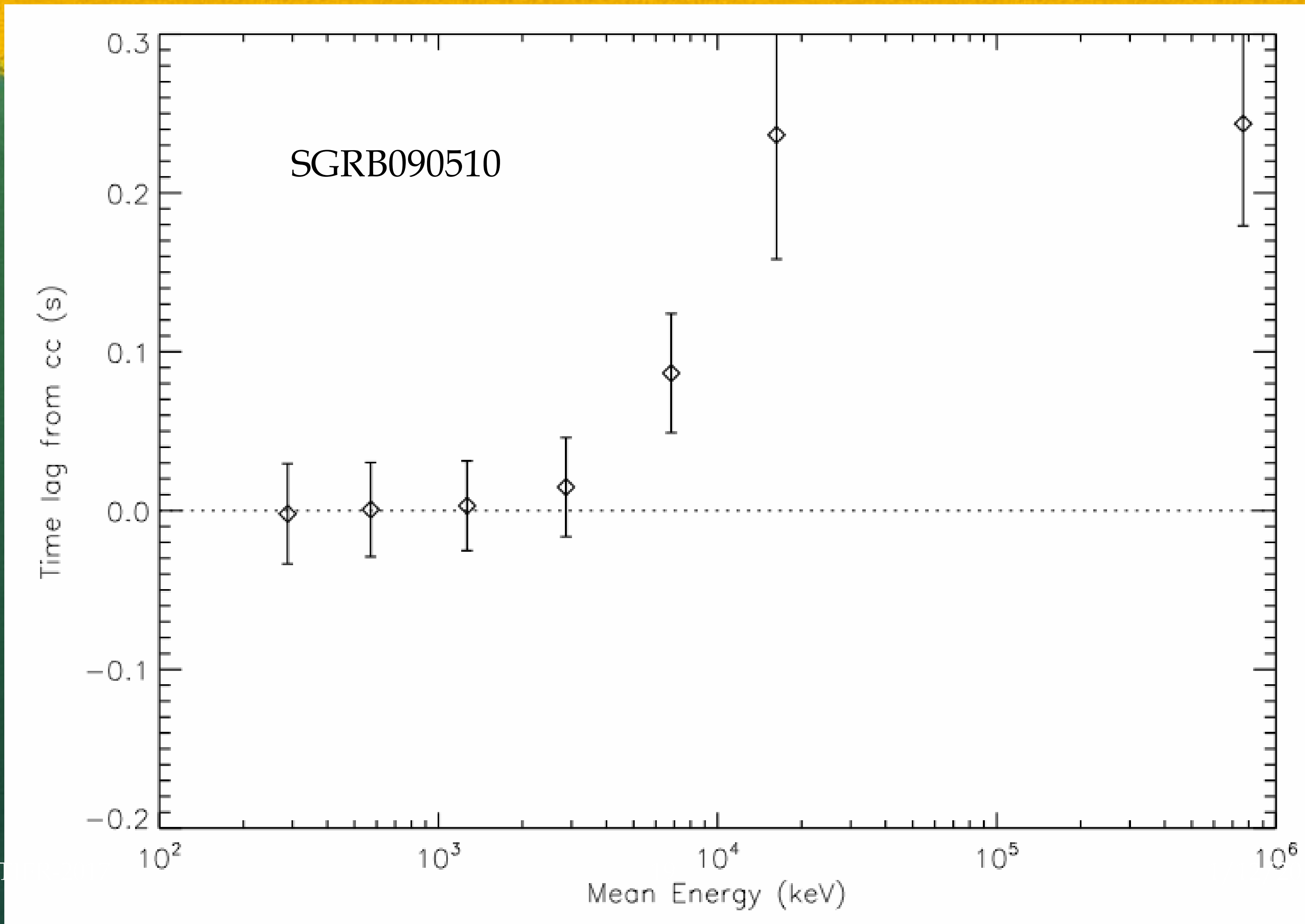
mean values of the observer-frame spectral lags using the Swift GRBs.

The Short GRBs often have zero lag while the long GRBs have finite lag.

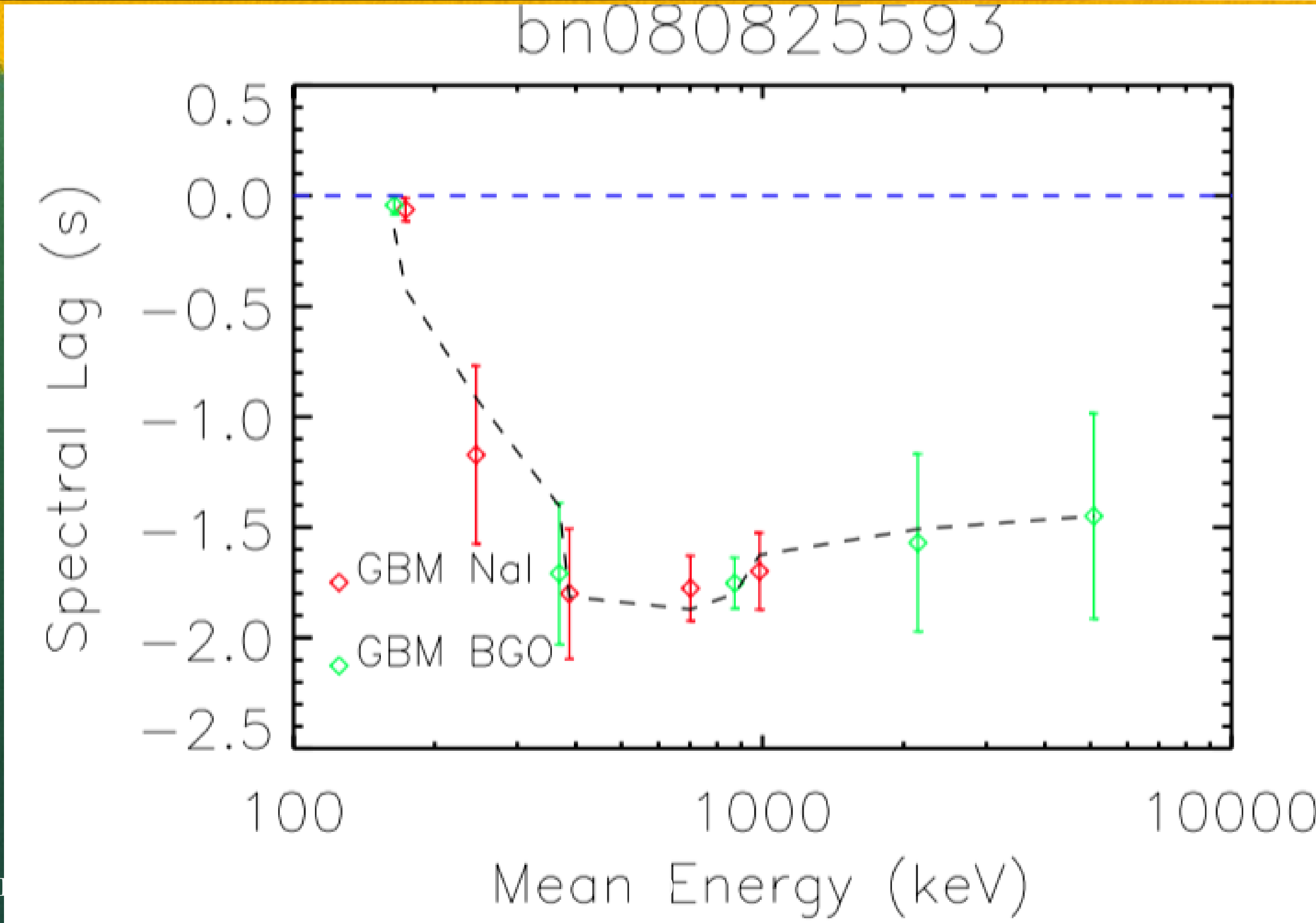




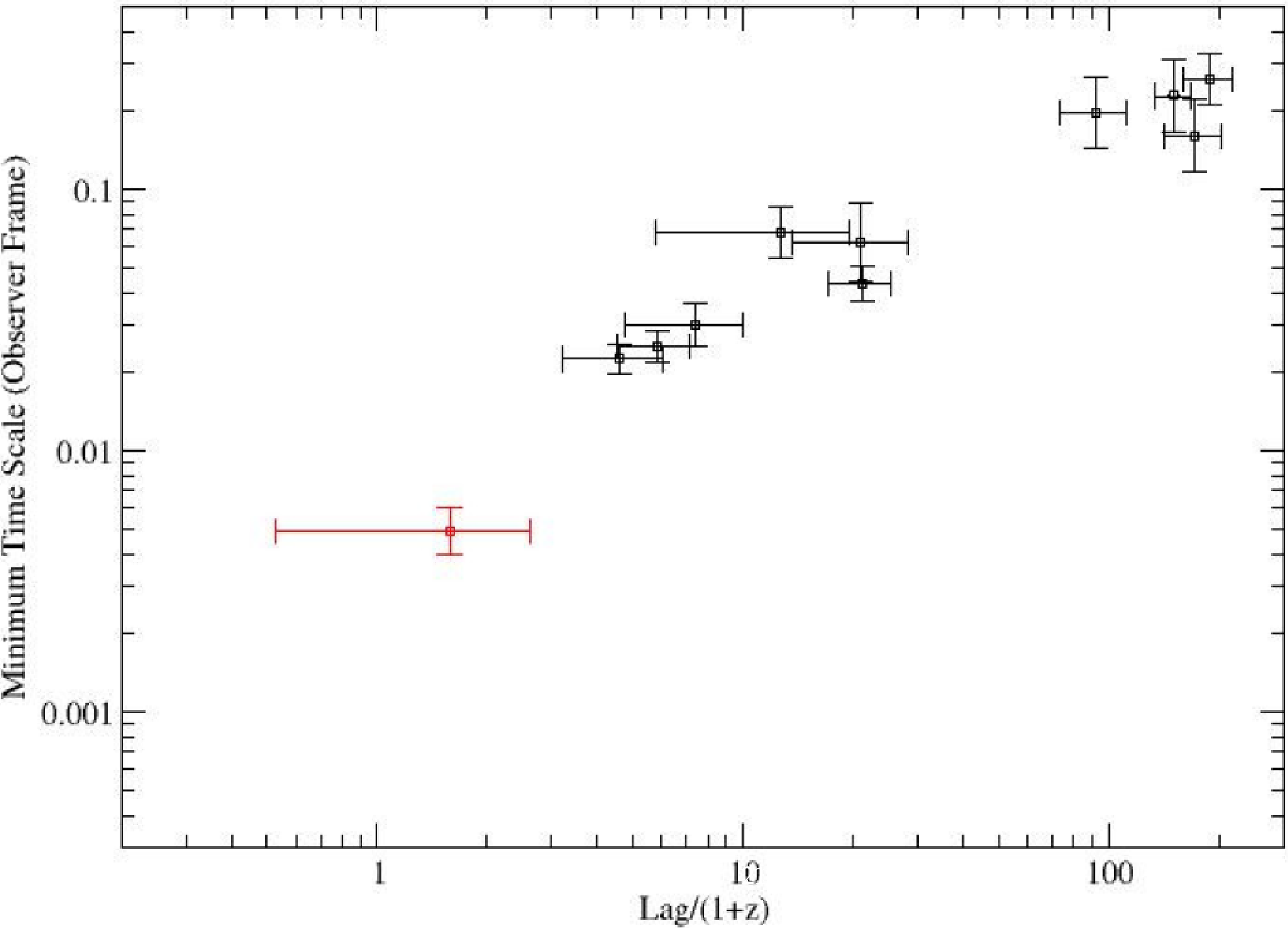
Spectral lags could arise due to the curvature effect of the shocked shell. At the source, the relativistically expanding shell emits identical pulses from all latitudes. However, when the photons reach the detector, on-axis photons get boosted to higher energy (hard). Meanwhile, off-axis photons get relatively smaller boost and travel longer to reach the detector. Thus, these photons are softer and arrive later than the on-axis photons.


SGRB090510
Time lag from cc (s)
0.3
0.2
0.1
0.0
−0.1
−0.2
10^2
10^3
10^4
10^5
10^6
Mean Energy (keV)

LGRB080825593



Lag dependence on MVT

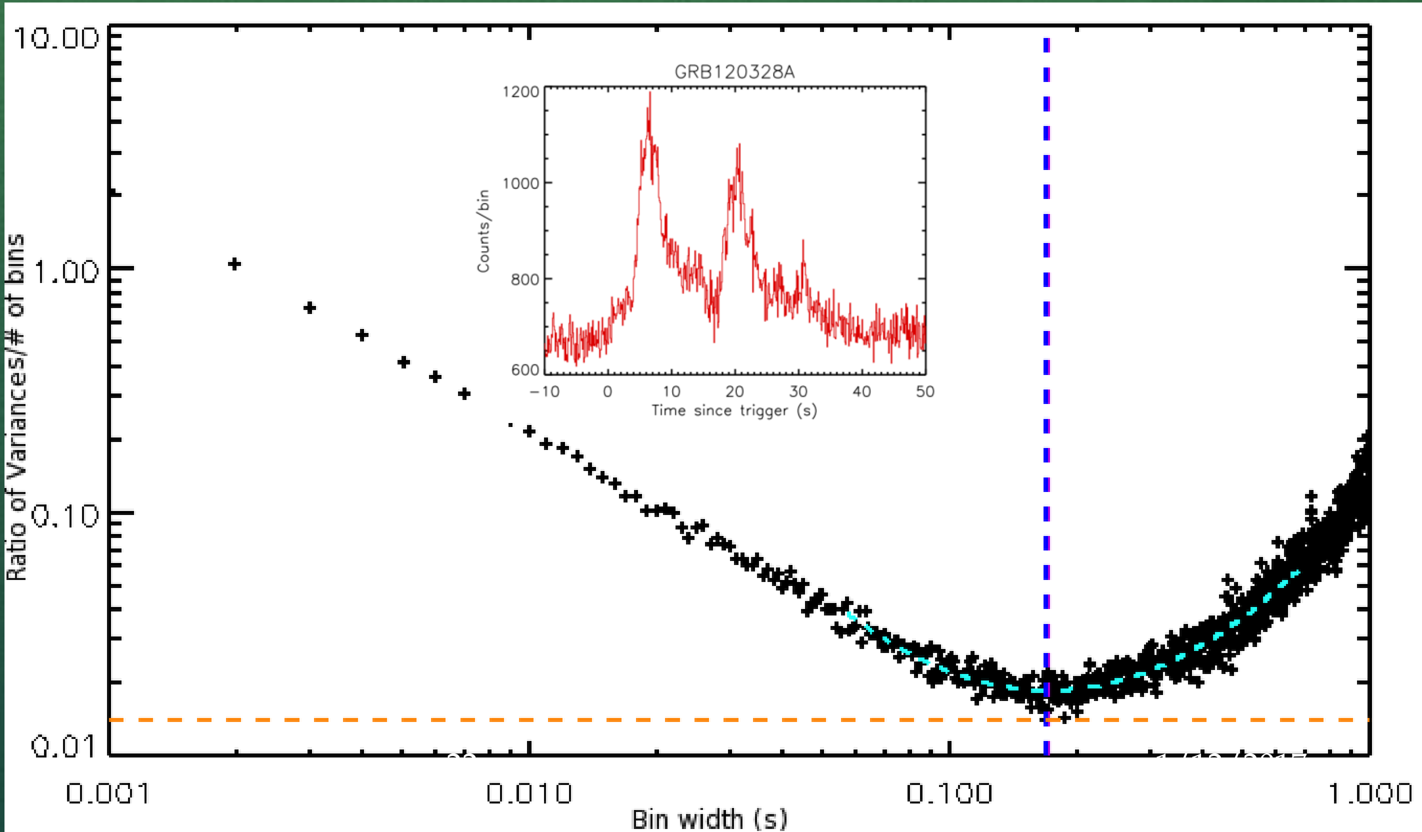


Spectral lags and minimum variability time scales are plotted for band 1. Red point indicates short GRB in the sample.

GRB Minimum Variability Time

Exploring the Extreme Universe

The light curve variability time scale is an interesting parameter which most models attribute to a physical origin e.g., central engine activity or relativistic turbulence. We develop a statistical method to estimate the GRB optimum bin-width, t_b, of GRBs which is consistent with the minimum variability time scale (t_v) for a sample of long and short GRBs detected by GBM.



A plot of the ratio of the variances of the differential of the burst and background light curves divided by a number proportional to the bin-width as a function of the the bin-width of the histogram for GRB120328A.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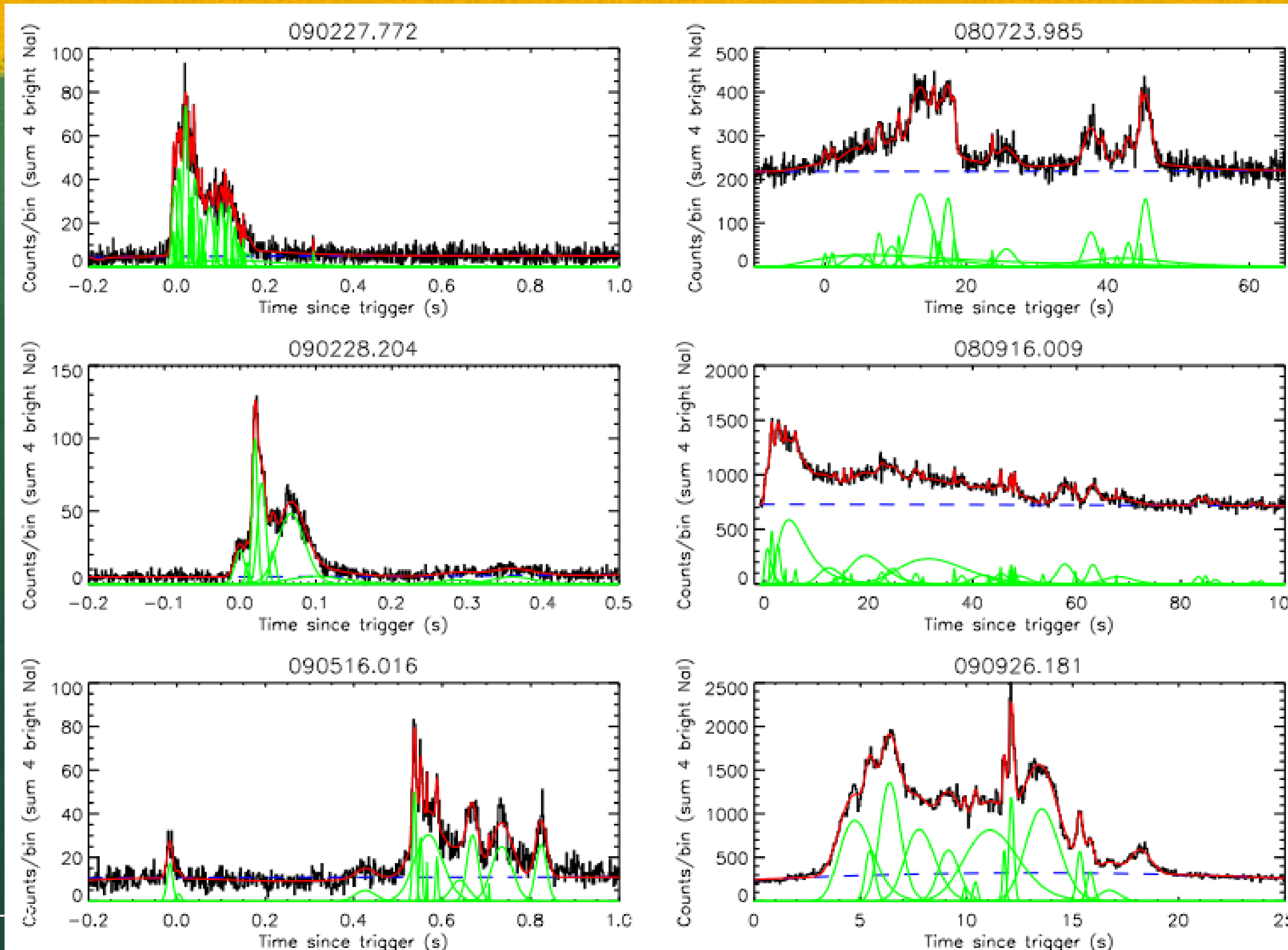
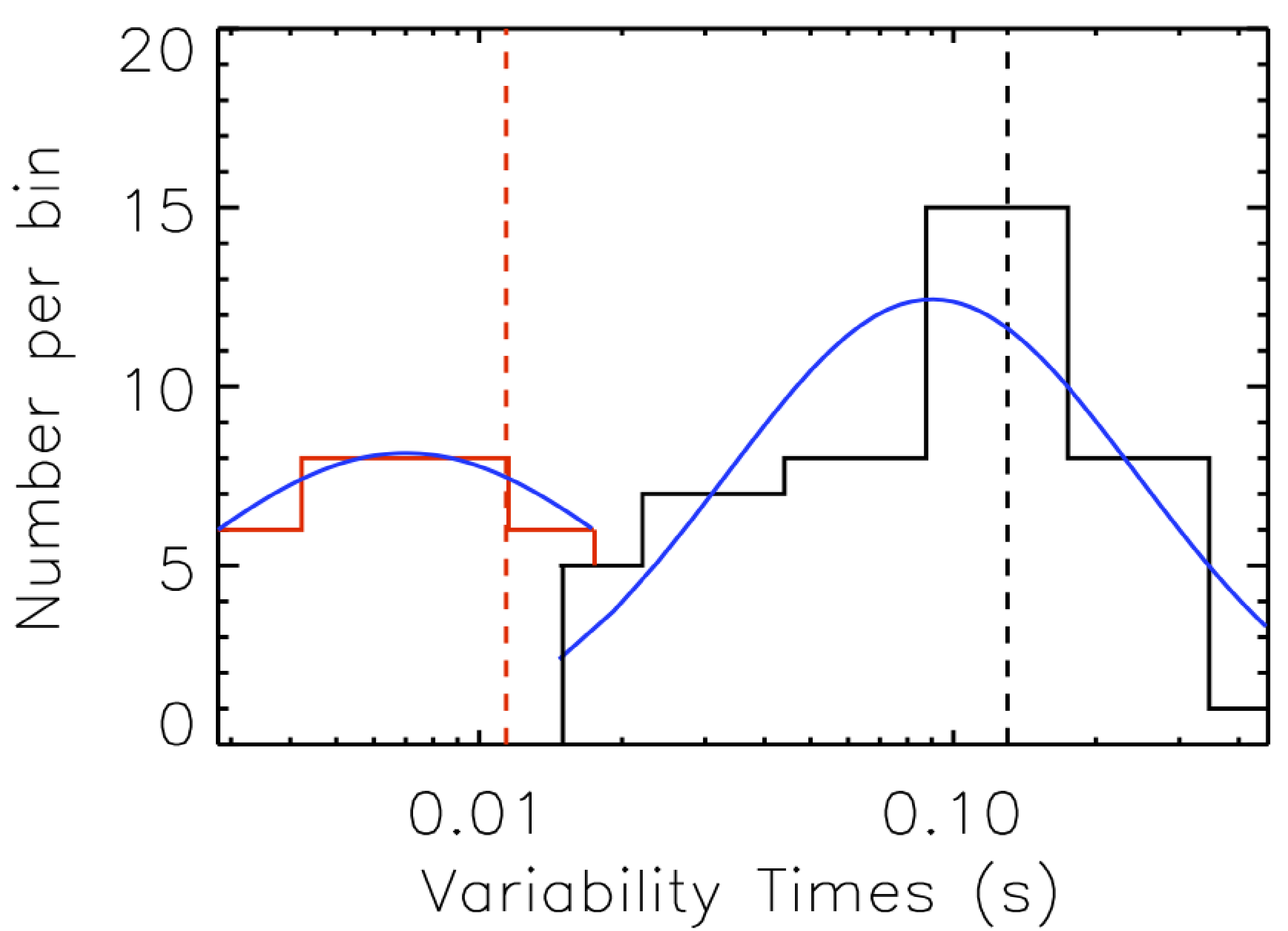
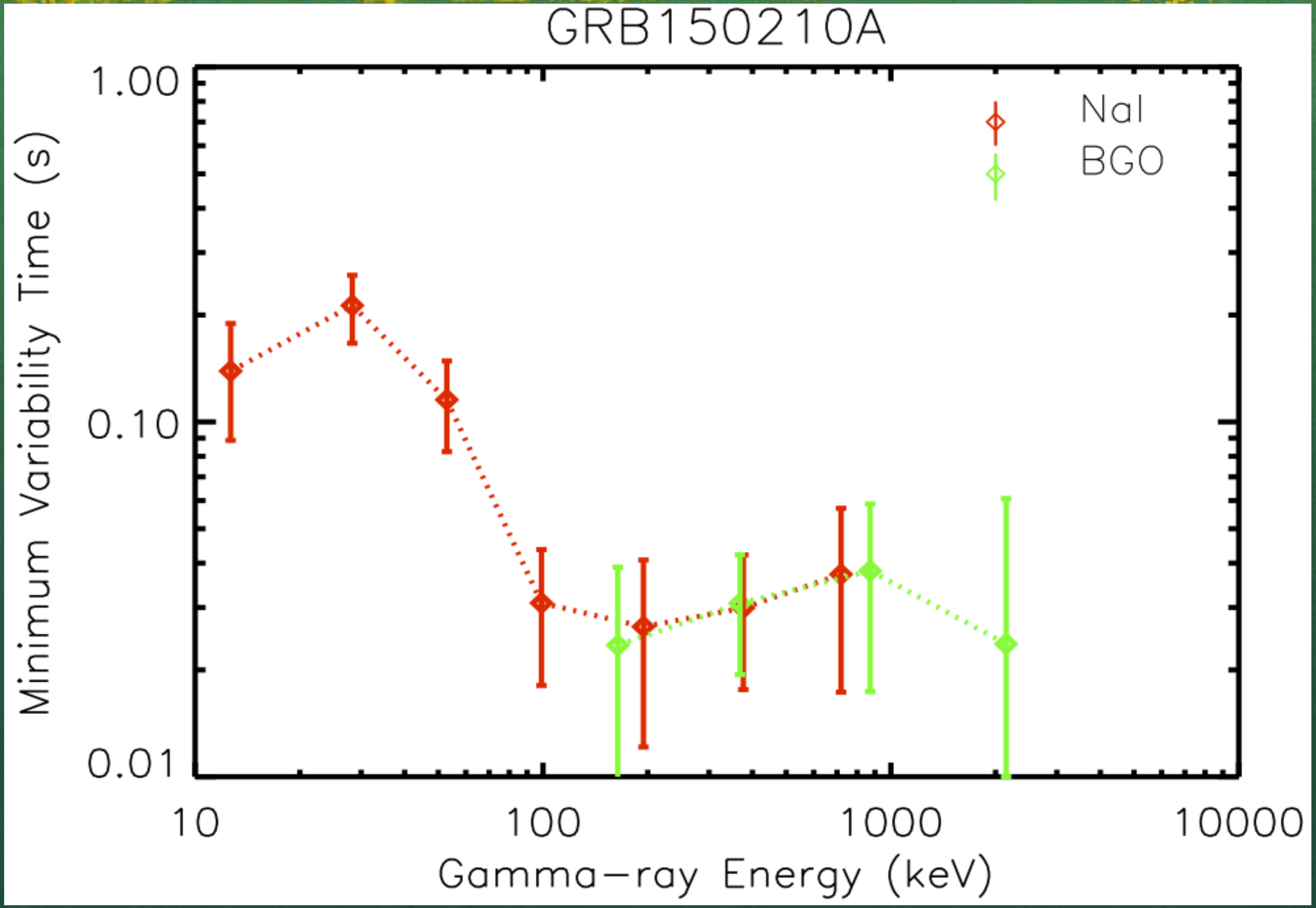
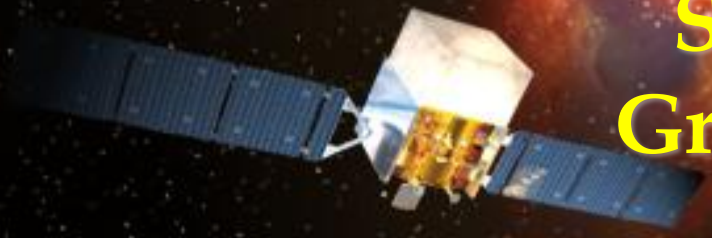

090227.772
080723.985
090228.204
080916.009
090516.016
090926.181
Counts/bin (sum 4 bright NaI)
Time since trigger (s)



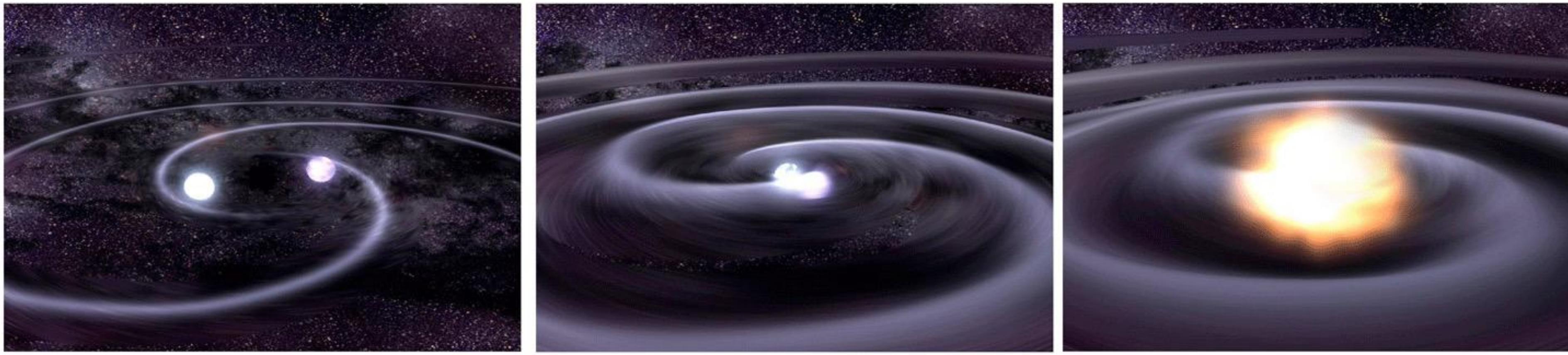
A distribution of the minimum pulse rise time for long and short GRBs. The minimum variability time scale or the minimum tted pulse rise time clearly shows a bimodal distribution showing that it can be a parameter to distinguish between long and short GRBs.


GRB150210A
NaI
BGO
Minimum Variability Time (s)
1.00
0.10
0.01
10
100
1000
10000
Gamma−ray Energy (keV)

Short GRB's and Gravitaional Waves



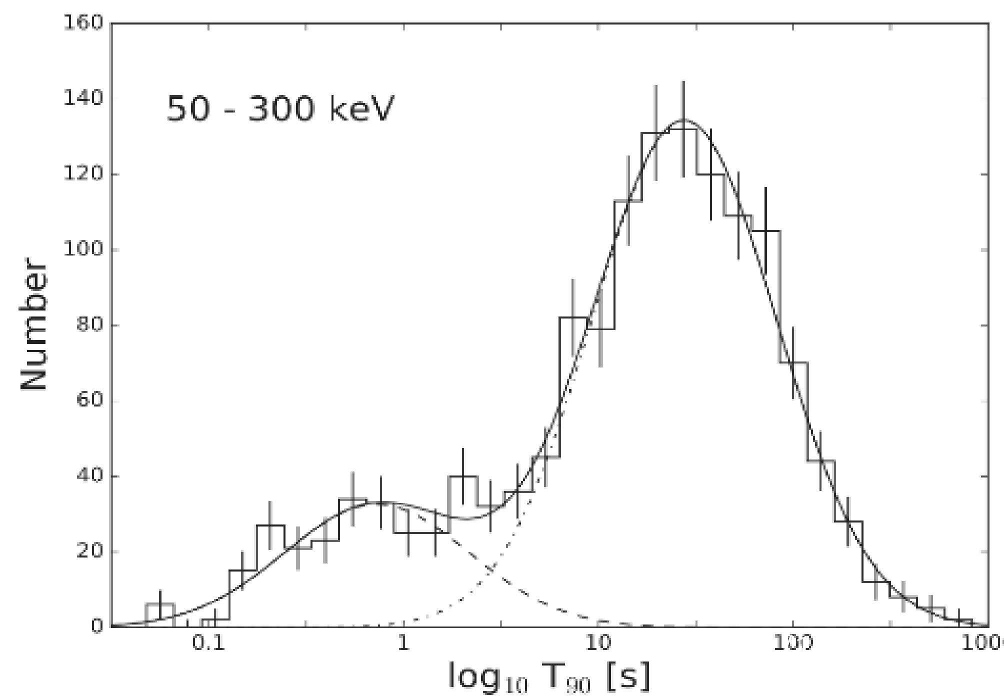
Exploring the Extreme Universe

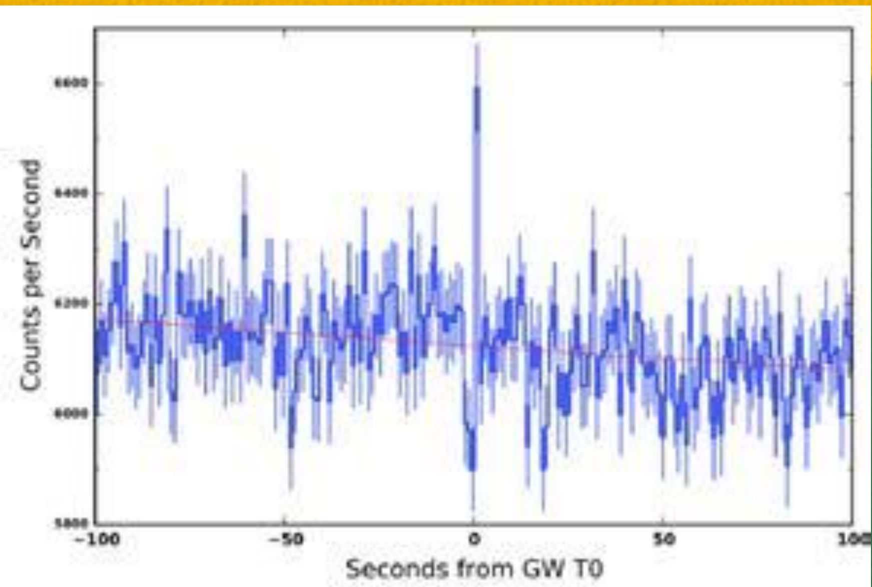


Fermi GBM is an all sky monitor of GRBs

- Short GRBs →NS-NS, NS-BH
- GBM: ~ 40 triggered short GRBs/year
- Swift: ~ 9 short GRBs/year

TIFR-2017





A possible untriggered sGRB 0.4 s After the GW event.

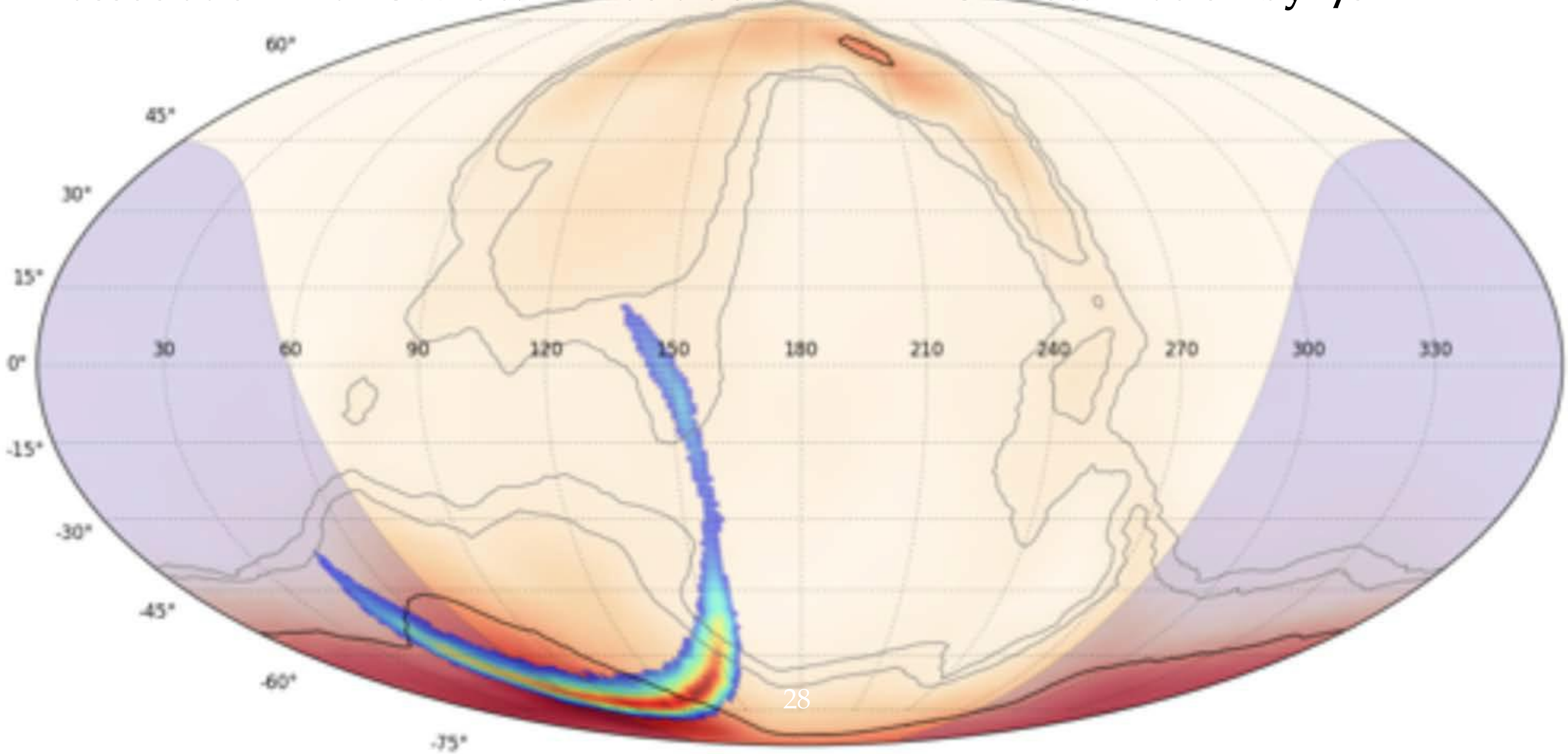
"Fermi GBM Observations of LIGO Gravitational-wave Event GW150914"Connaughton, V., et al. 2016, ApJ, 826, L6

σ deviation from a background fit

NaI 0	NaI 1	NaI 2	NaI 3	NaI 4	NaI 5
1.31	1.81	0.64	1.05	2.42	1.68
NaI 6	NaI 7	NaI 8	NaI 9	NaI 10	NaI 11
1.31	1.64	1.45	2.20	1.61	0.66
BGO 0	BGO 1				
2.25	2.56				

Unusual detector pattern: nearly equal count rates in all NaI etectors

- Localization: source direction **underneath** the spacecraft, 163°to the spacecraft pointing direction
- If association with GW150914 was true: **shrink LIGO localization by 2/3**



GW Association?

Fermi Gamma-ray Space Telescope

Exploring the Extreme Universe

- **Evidence for:**
  - 3 sigma False Alarm Probability
  - GBM signal localized to a region consistent with the LIGO sky map
  - Cannot be attributed to other known astrophysical, solar, terrestrial or magnetospehric activity

- **Evidence against:**
  - Low significance
  - Lack of corroboration by other experiments
  - Nature of the LIGO event is a BH-BH merger

	Duration	Localization	Energy Spectrum	Lightcurve Shape	Fermi Orbit Position	Origin?
Lightning (TGFs/TEBs)	No	No	?	No	No	No
Galactic Sources	?	No	No	?	N/A	No
Magneto spheric	No	?	?	No	No	No
Solar Activity	?	No	No	No	N/A	No
Something New	?	?	?	?	?	Maybe? Unlikely
Short GRB	Yes	Yes	Yes	Yes	N/A	Yes

MOST LIKELY

fermi Gamma-ray Space Telescope

Summary

Exploring the Extreme Universe

- Energy band-width is vital to study hitherto unknown physics of GRBs.
- All GRBs do not fit the standard Band spectrum without additional components which become necessary when the data from a larger energy band-width are available.
- The origin of the some of the spectral components is still unknown.
- High energy signals in some GRBs are consistent with after-glow produced by the external shock.
- Bimodality of Burst durations are strictly valid in the limited 50-300 keV energy range.
- T_{90} in general seem to fall with increasing energy but much less steeply than thought before.

Summary (contd.)

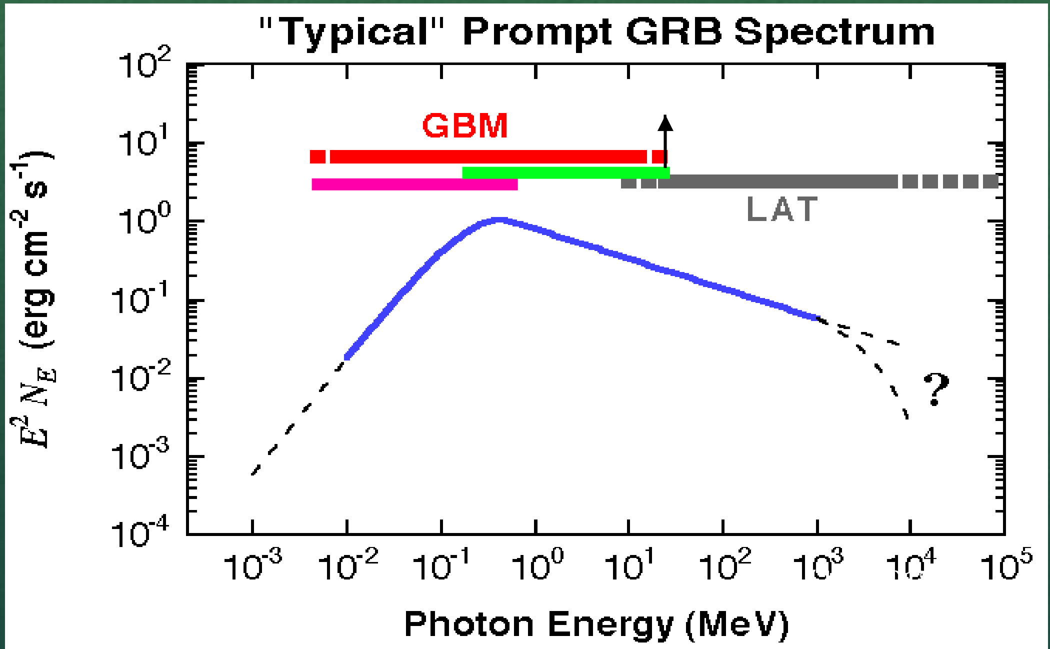
- Spectral lags in some short and long bursts seem to change sign at several MeV energies hinting at a different physics for the production of high energy photons.
- At lower energies short busts exhibit small or no spectral lag while long GRBs do exhibit larger lags.
- Minimum variability times of GRBs show a bi-modal behavior consistent with short bursts being more compact compared to long GRBs.
- While generally variability increases with energy individual bursts exhibit lot of diversity.
- One possible short burst has been detected by GBM 0.4s after the first gravitational wave event.
- If this is indeed is the electromagnetic counter-part of GW's it poses more questions than it solves.

Backup Slides

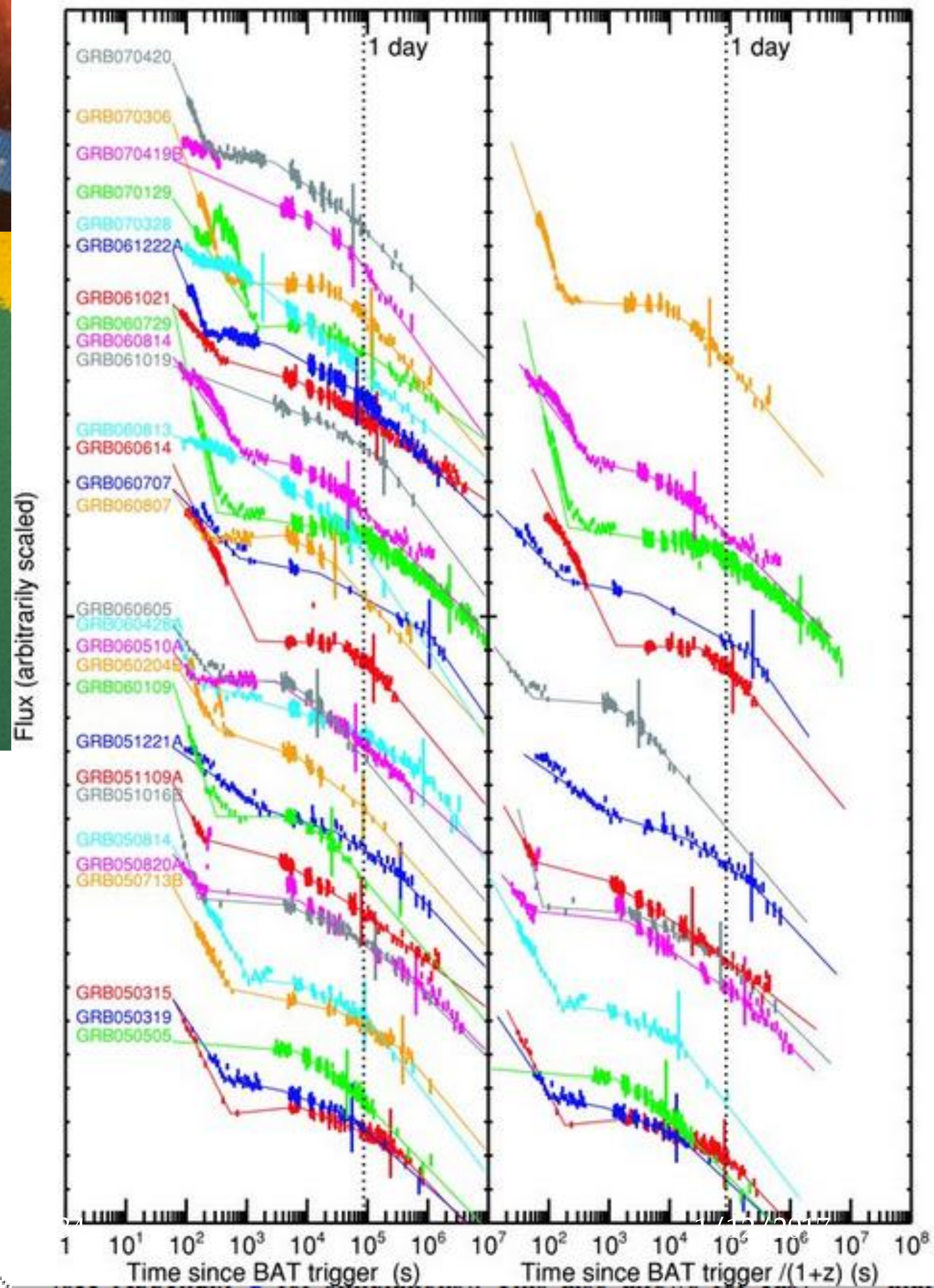
Fermi and GRB

- **LAT: <20 MeV to >300 GeV. With both onboard and ground burst triggers.**
- **GBM: 12 NaI detectors— 8 keV to 1 MeV. Used for onboard trigger, onboard and ground localization, spectroscopy: 2 BGO detectors— 150 keV to 45 MeV. Used for spectroscopy.**
- **Total of >7 energy decades!**
- **Expected ~240 GRB/year with observations from 8 keV to 30 MeV, ~80 GRB/year with observations from 8 keV to 300 GeV (# high energy detections is under study)**

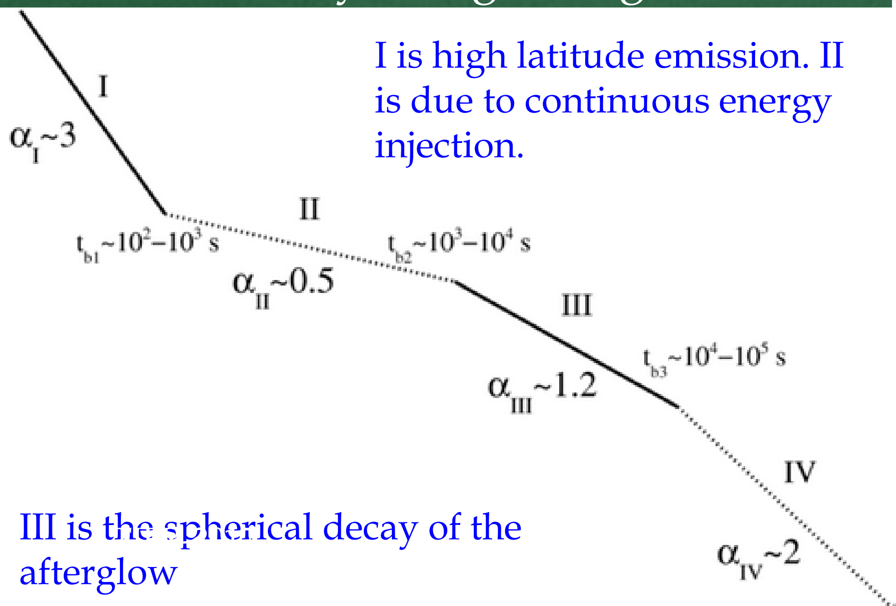
Exceptionally good spectral observations of the prompt phase of lots of GRB



Arbitrarily scaled light curves and temporal fits for all Prominent jet breaks in the observed frame (left) and rest frame (right, where available). The final light curve break is indicated by the vertical line in the same color as the light curve and fit.

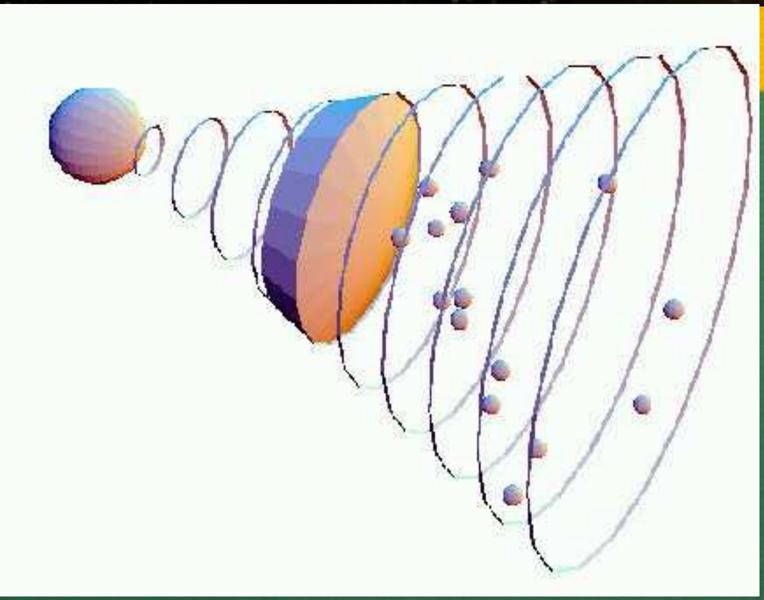


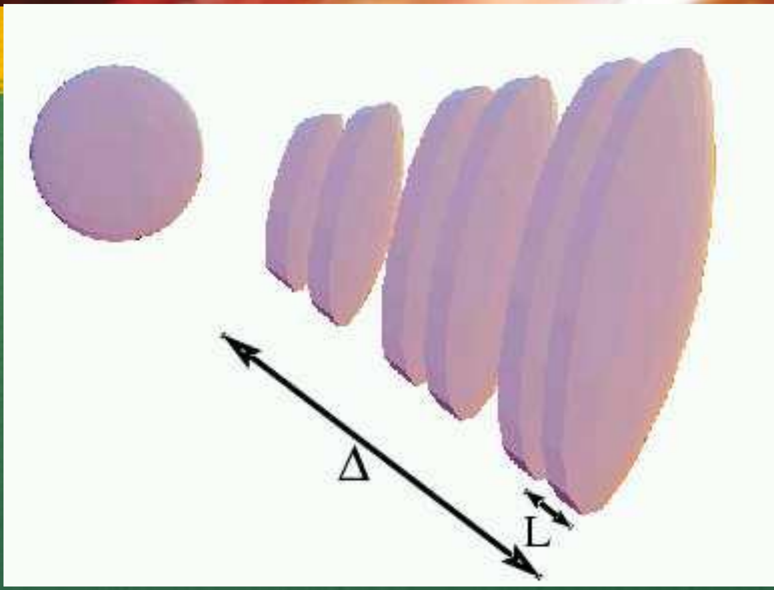
Canonical X-ray afterglow light curve



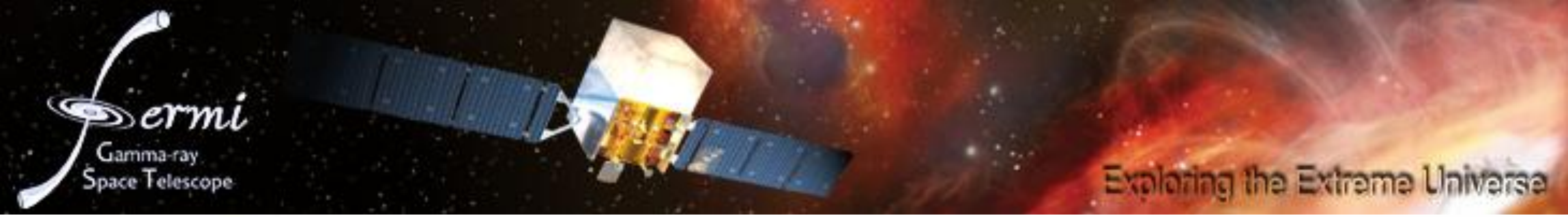
I is high latitude emission. II is due to continuous energy injection.

III is the spherical decay of the afterglow





Producing variability by external shocks (left) or internal shocks (right). In the external shocks scenario, the variability is produced by irregularities in the surrounding. If the surrounding consists of a low density medium that contains high density clouds, then whenever the shell hits one of the clouds a peak in the emission is produced. The number of clouds within the observable cone (of angular size $1/\Gamma$ due to relativistic beaming) should therefore roughly be the number of observed peaks.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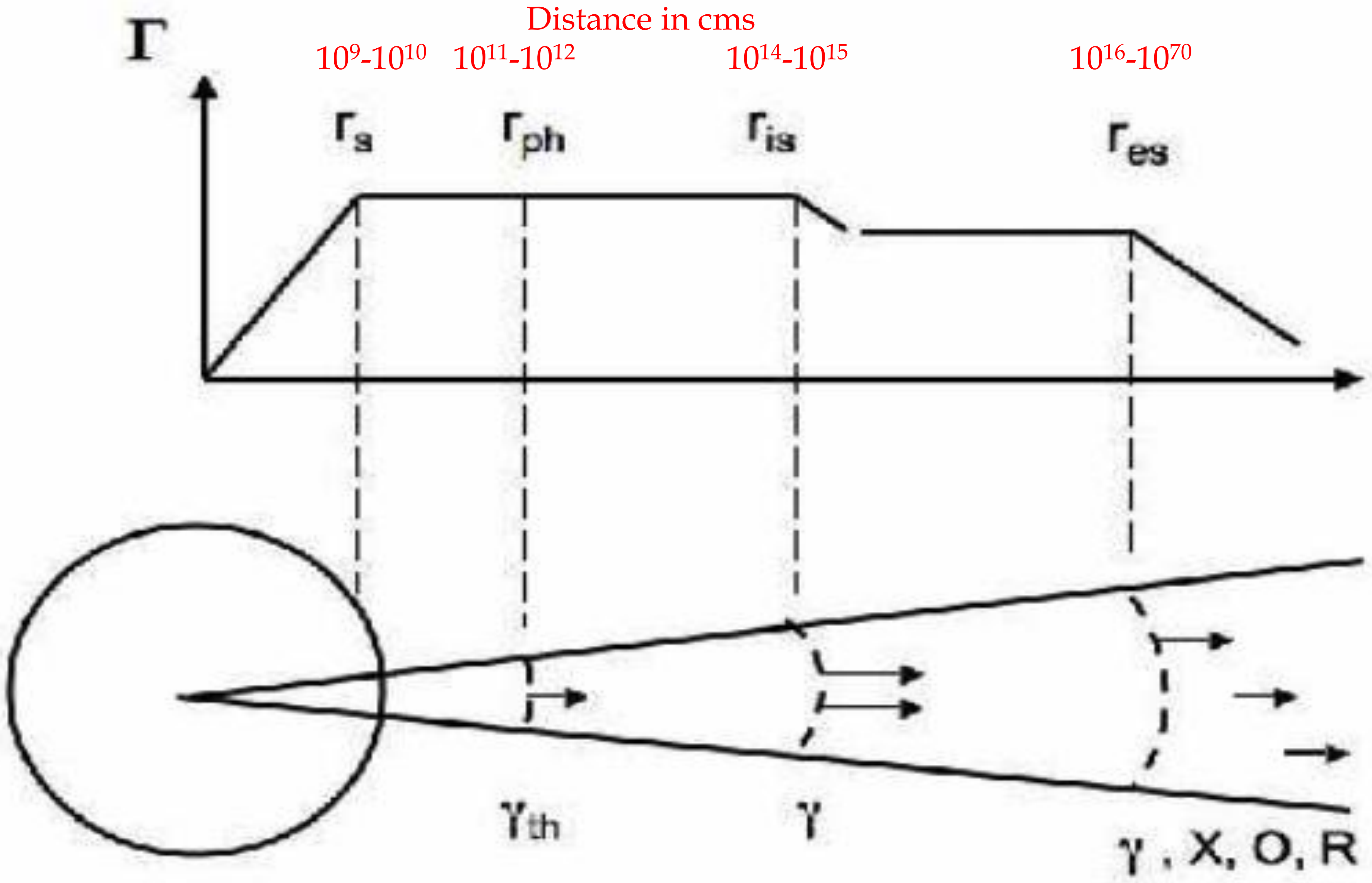
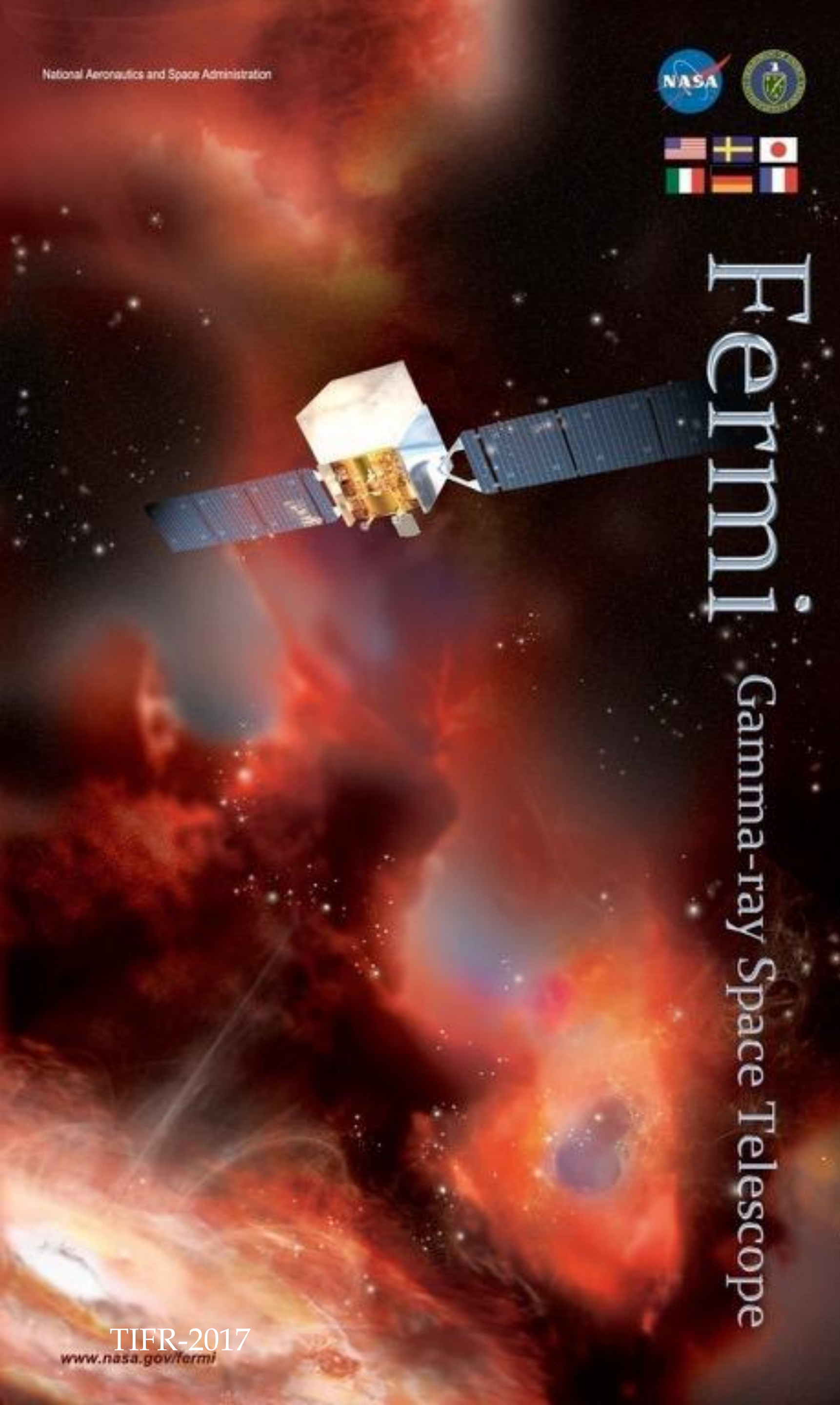
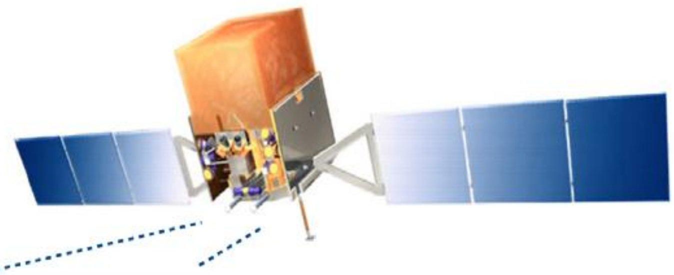
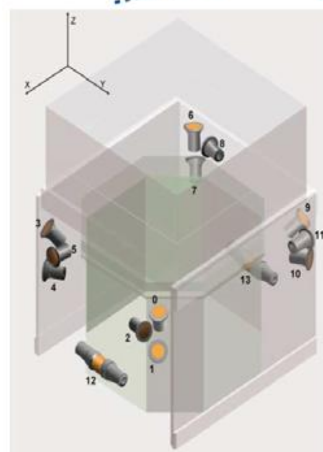

Distance in cms
10^9-10^{10}
10^{11}-10^{12}
10^{14}-10^{15}
10^{16}-10^{70}
Γ
r_s
r_{ph}
r_{is}
r_{es}
γ_{th}
γ
γ, X, O, R



Fermi Gamma-ray Burst Monitor [10] (GBM)





GBM consists of an array of:
- *12 NaI scintillation detectors < 1 MeV*
- *2 BGO detectors < 40 MeV*

Bursts are seen as coincident excess over background in multiple detectors
- *smooth background fit*
- *coincidence rejects noise*
- *relative rates determine source location*

Continuous production of offline (daily) data products
- *CTIME: (0.256s, 8 channels) for high time resolution*
- *CSPEC: (4s, 128 channels) for high spectral resolution*
- *TTE: (2µs, 128 channels) for detailed time and spectral resolution*
  continuous archiving of TTE data starting end of 2012

Gamma-ray Burst Monitor Catalogs

- The **3rd Fermi GBM Gamma-ray Burst** Catalog: The First Six Years
  Bhat, P.N. et al., ApJSS, 223, 28 (2016)

- GRB **time-resolved spectral** catalog: The brightest bursts in the first 4 years
  Yu, H.-F. et al., A&A, 588, A135 (2016)

- The Fermi-GBM **Three-year X-ray Burst**Catalog
  Jenke, P.A. et al., ApJ, 826, 228 (2016)

- First GBM **TGF catalog**:
  Fitzpatrick, G. et al., in preparation

- The **Five Year Fermi/GBM Magnetar Burst** Catalog
  Collazzi A.C. et al., ApJ, 218, 11 (2015)

Other results: Earth occultation monitoring, Pulsar Monitoring, …

▪**GBM Observations of GW Event Counterparts** Untriggered & Targeted Search
GW150914, LVT151012, GW151226

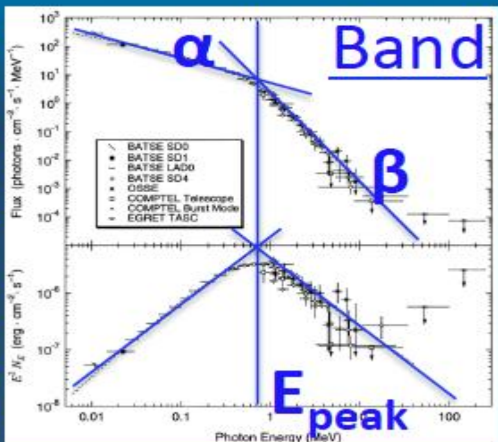
GRB Spectral Analysis

Fermi Gamma-ray Space Telescope

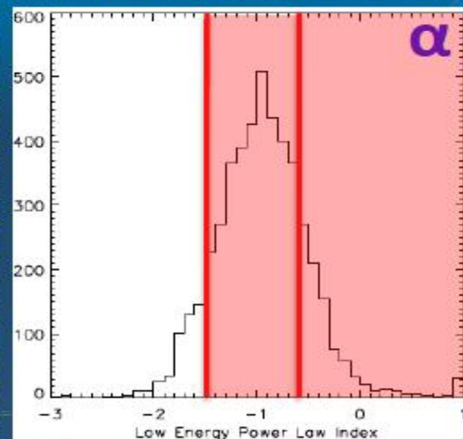
Exploring the Extreme Universe

In the CGRO Era

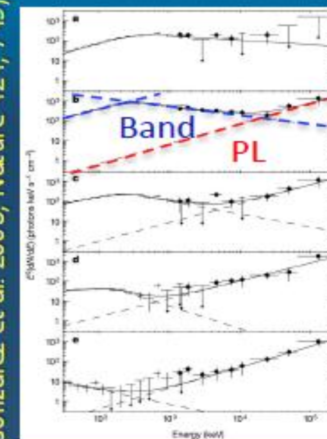
(Briggs et al. 1999, ApJ, 524, 82-91)



(Preece et al. 2000, ApJS, 126, 19-36)



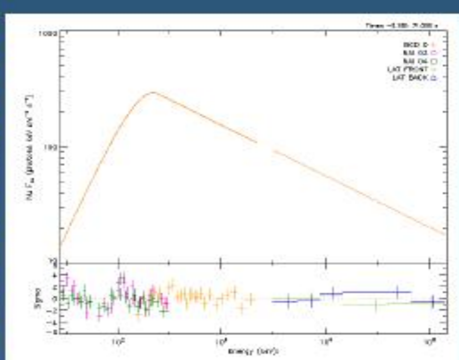
(Gonzalez et al. 2003, Nature 424, 749)



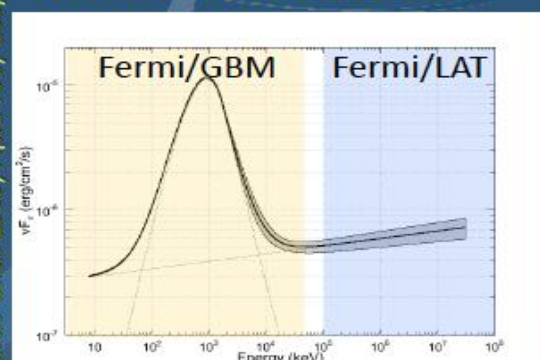
- Most likely synchrotron emission from e^- propagating and accelerated in the jet.
- Additional PL not compatible with synchrotron emission.

In the Fermi Era

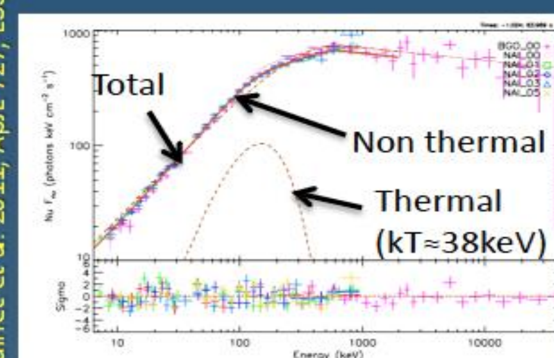
(Abdo et al. 2009, Science, 323, 1688A)



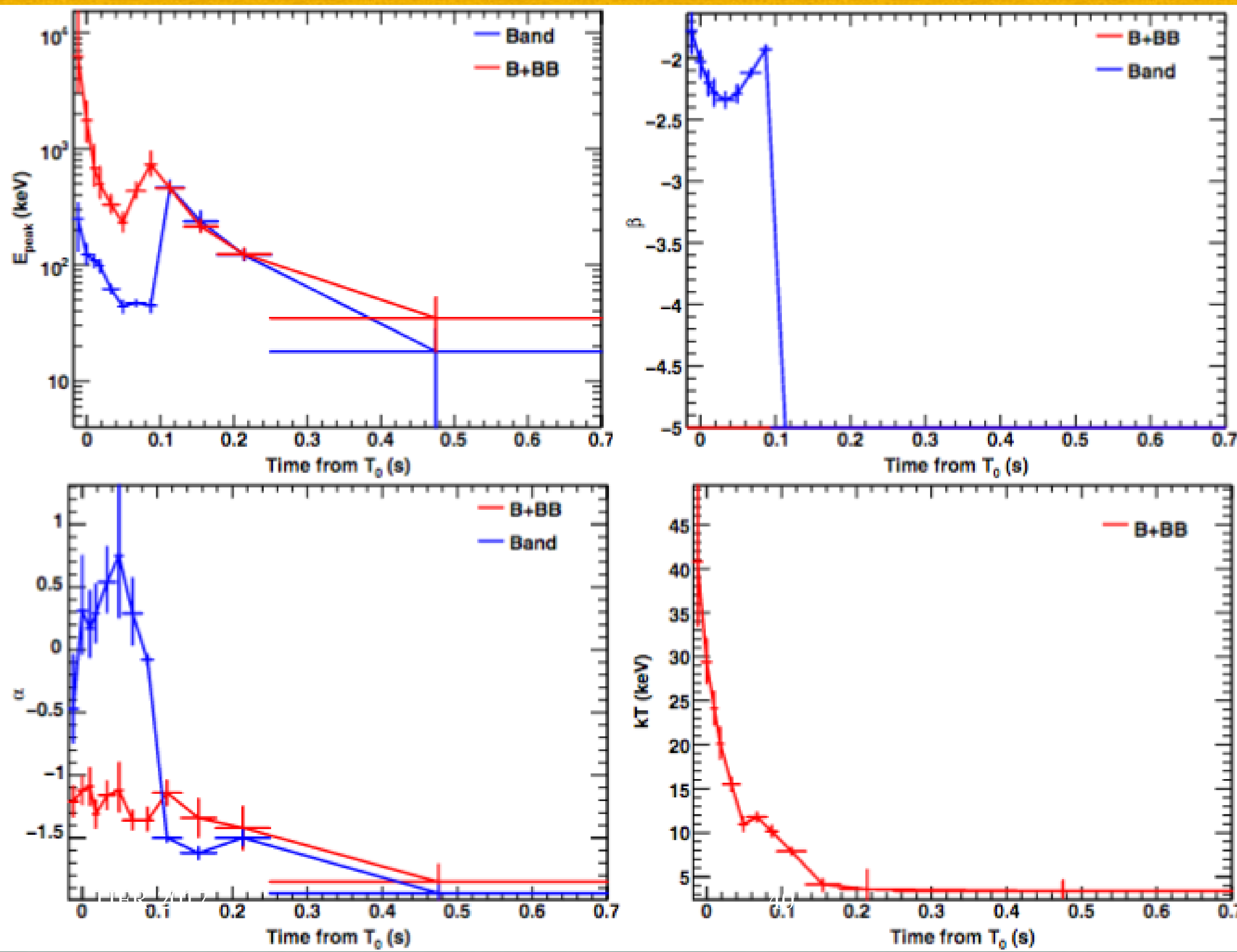
(Abdo et al. 2009, ApJL 706, 138)



(Guiriec et al. 2011, ApJL 727, L33)



- Additional PL extending from low to high energy challenges both leptonic and hadronic models.
- Thermal emission interpreted as jet photospheric emission.

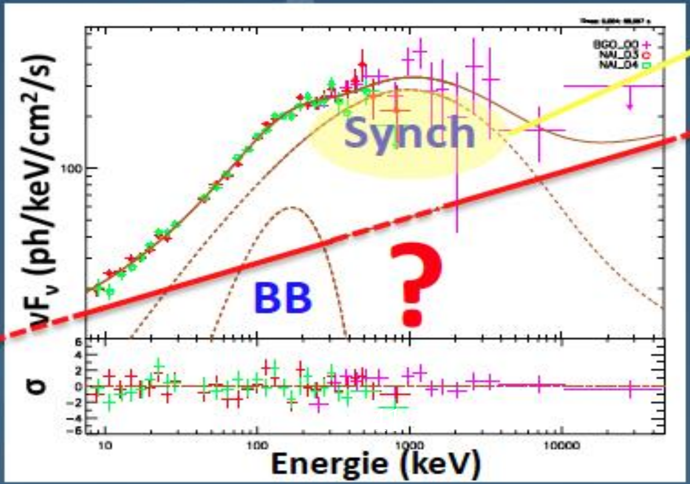


Evolution with time of the parameters of the spectral fits using the shortest time intervals. The blue lines correspond to the Band-only fit to the data and the red lines correspond to the B+BB fits.

- **Prompt emission spectra of GRBs are much more complex that the Band function usually used in the BATSE Era.**
- **With Fermi, we start to fit physical models to the spectra while only empirical models were used previously.**
  - **For the first time, we clearly identified a thermal component in addition to the non-thermal Band function.**
  - **Using the BB component, the Band function parameters are usually more compatible with synchrotron models.**
  - **Interpretation of the additional PL remains challenging for the physical models (need SVOM and CTA ?).**

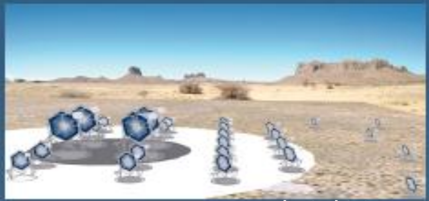
SVOM

Synch model + BB + PL

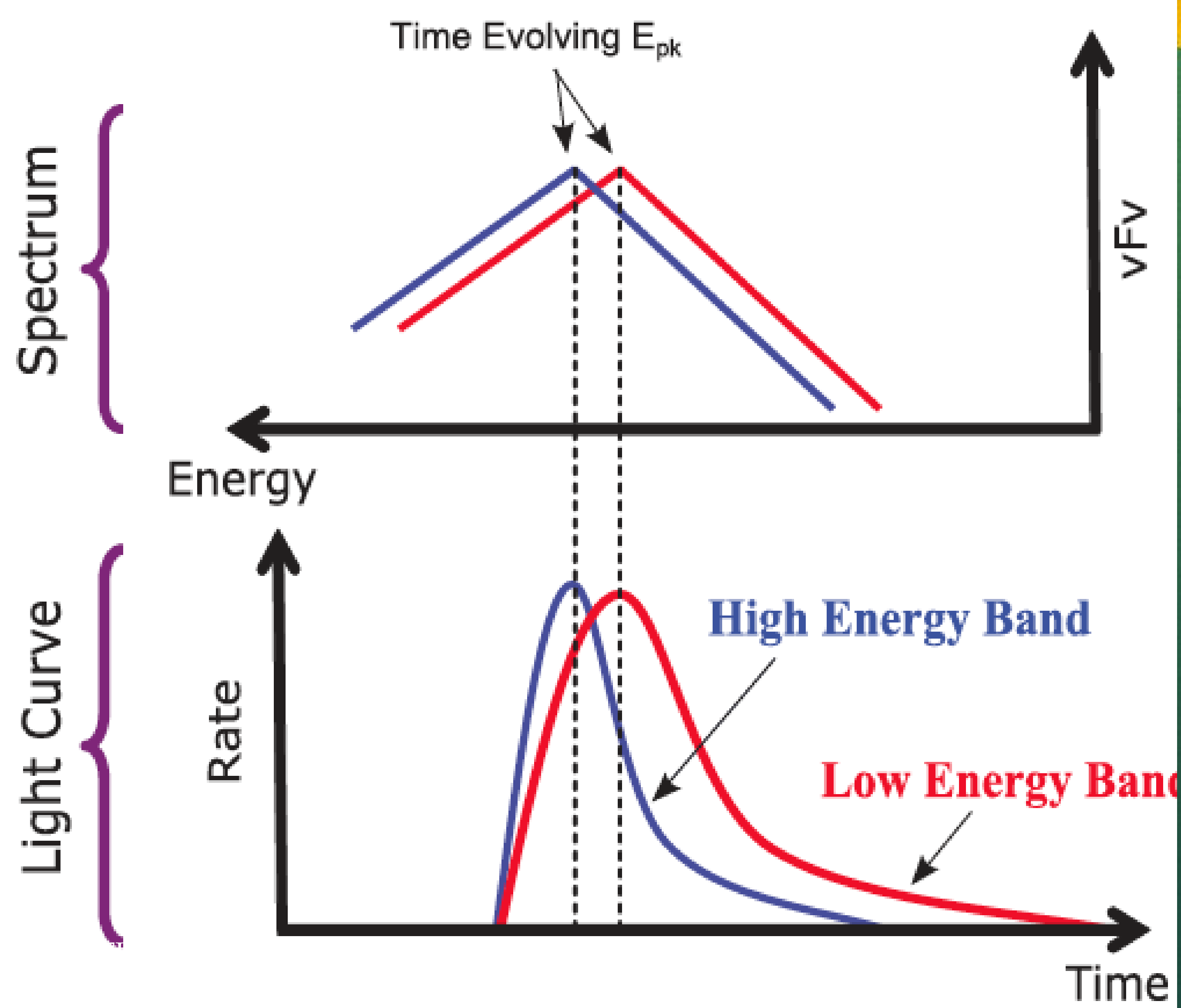


(Burgess et al. 2011, in press)

CTA

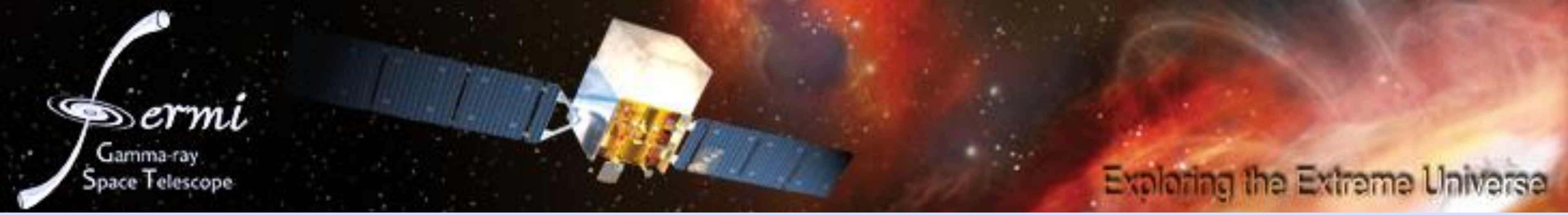


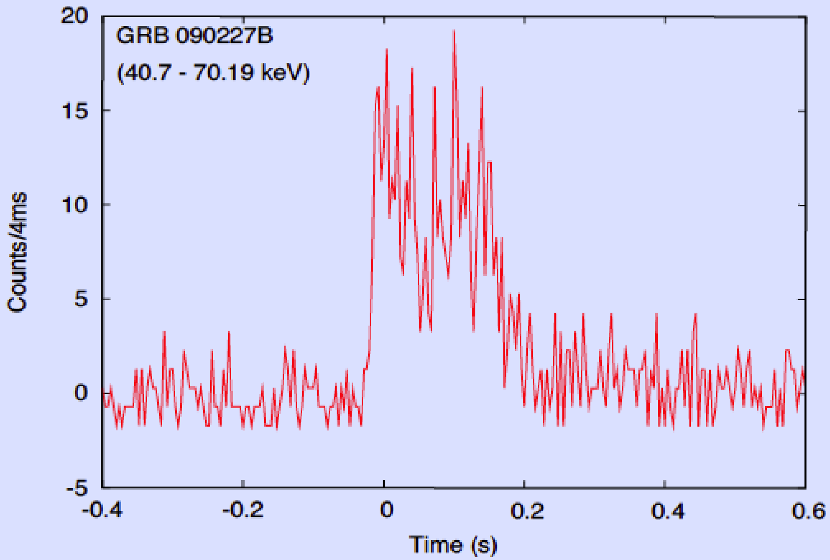
GRB Spectral Lags

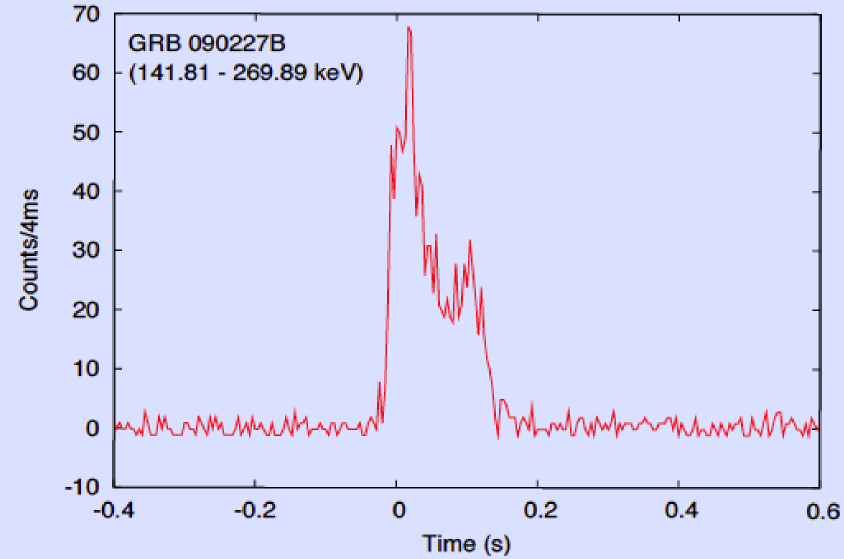


The time evolution of the E_{pk} across energy bands may cause the observed spectral lags in GRBs.

(1) the calculated cooling times based on simple synchrotron models
are, in general, relatively small compared to the extracted lags and
(2) short bursts which exhibit considerable spectral evolution do not







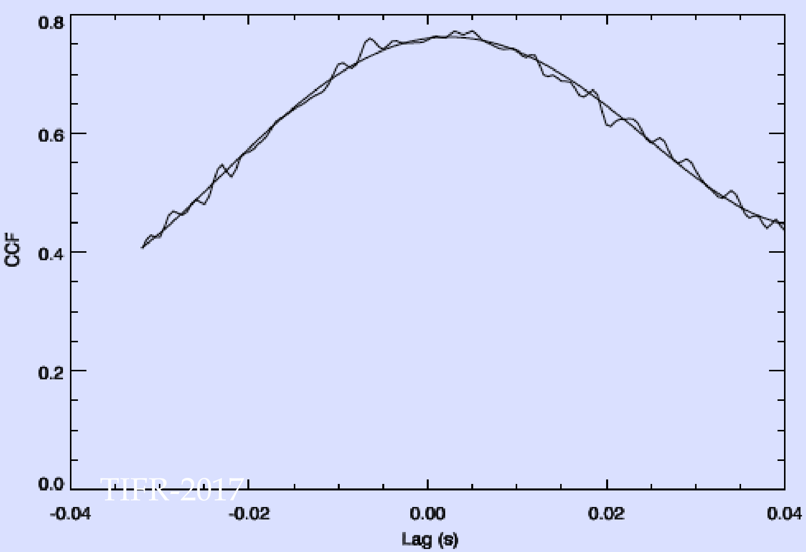
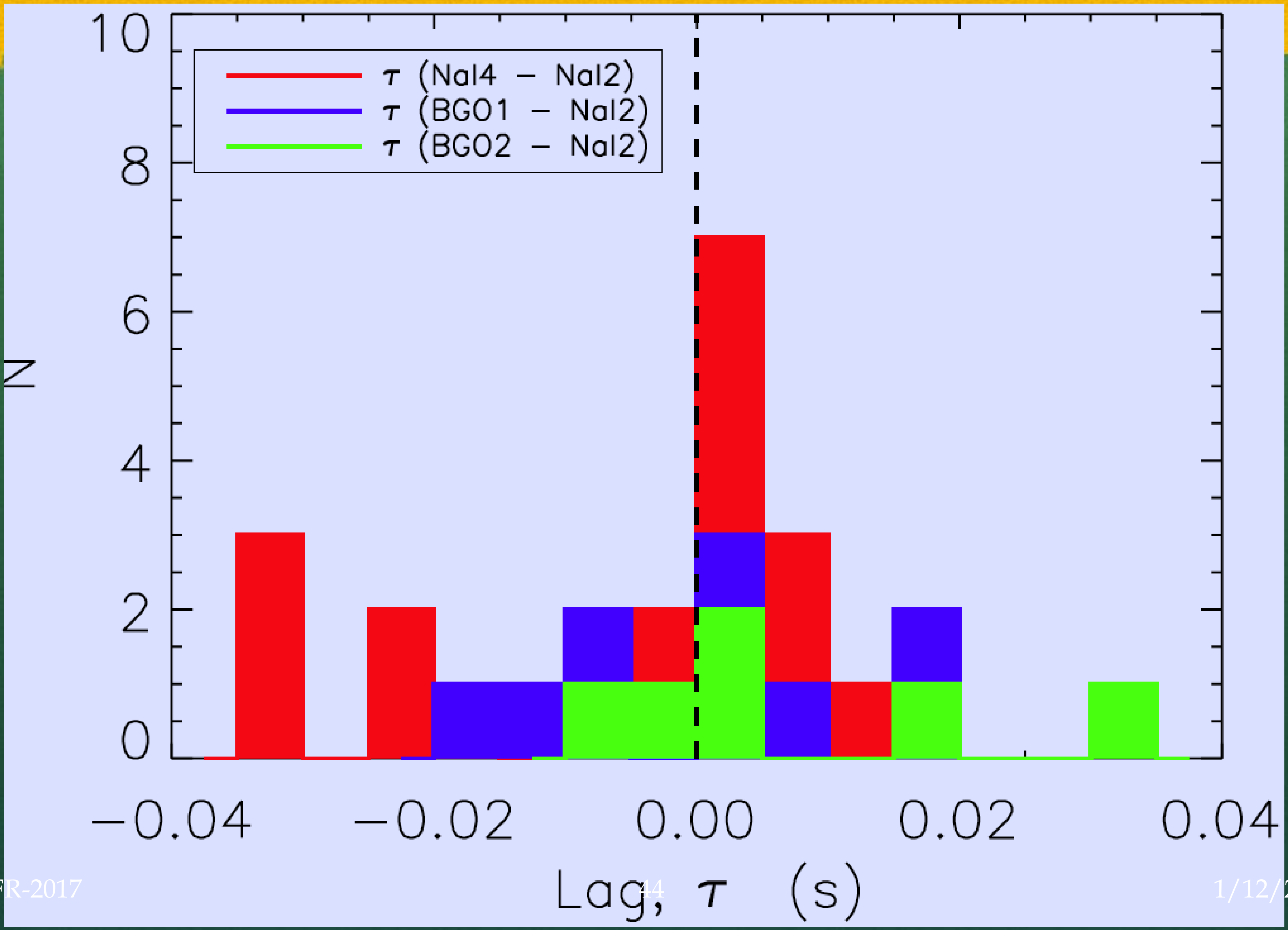
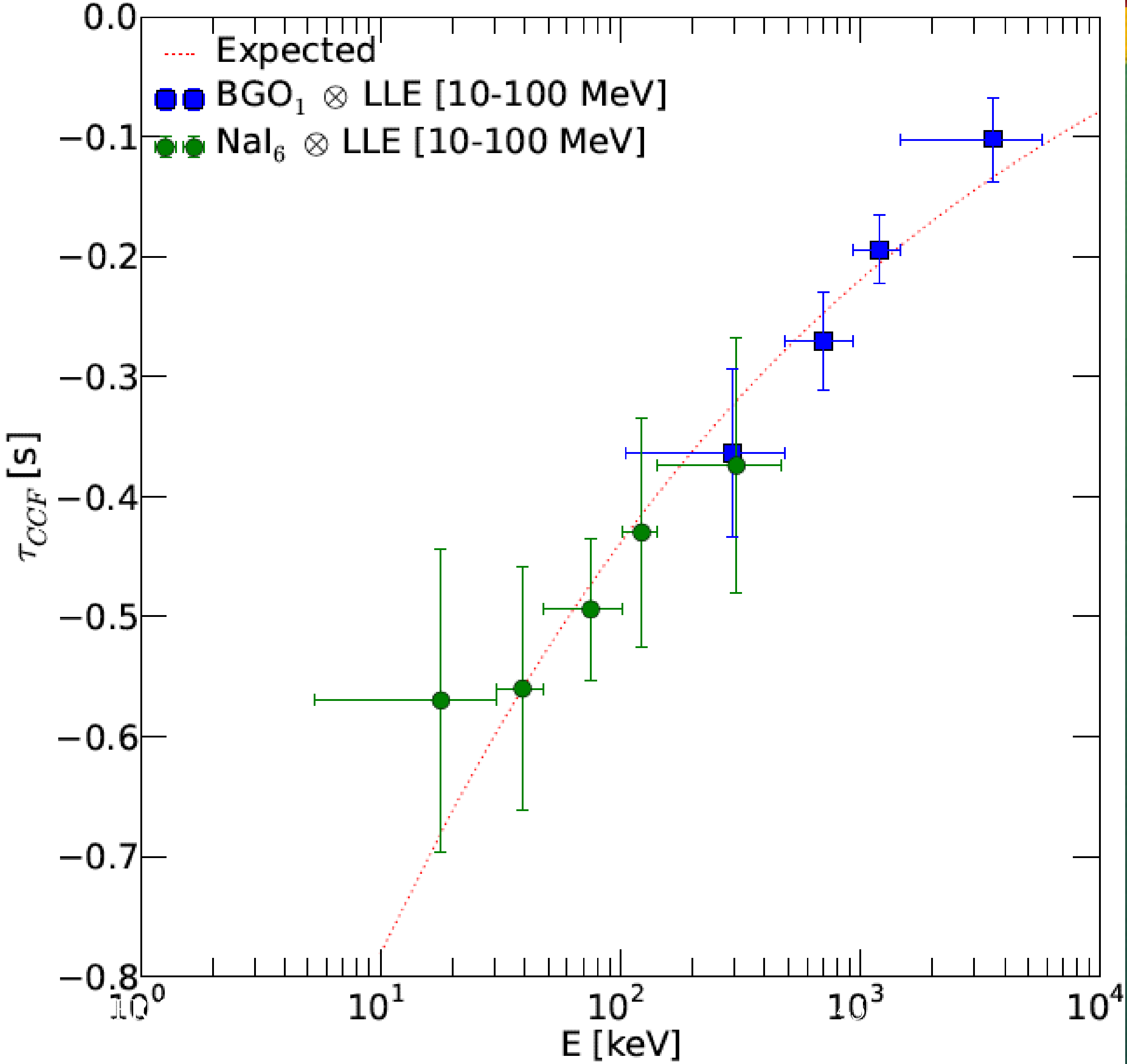


Figure 1: Lightcurves of GRB090227B in the 40.7 - 70.19 keV and 141.81 - 269.89 keV energy ranges and the resulting cross-correlation function.


10
8
6
4
2
0
N
τ (NaI4 − NaI2)
τ (BGO1 − NaI2)
τ (BGO2 − NaI2)
−0.04
−0.02
0.00
0.02
0.04
Lag, τ (s)

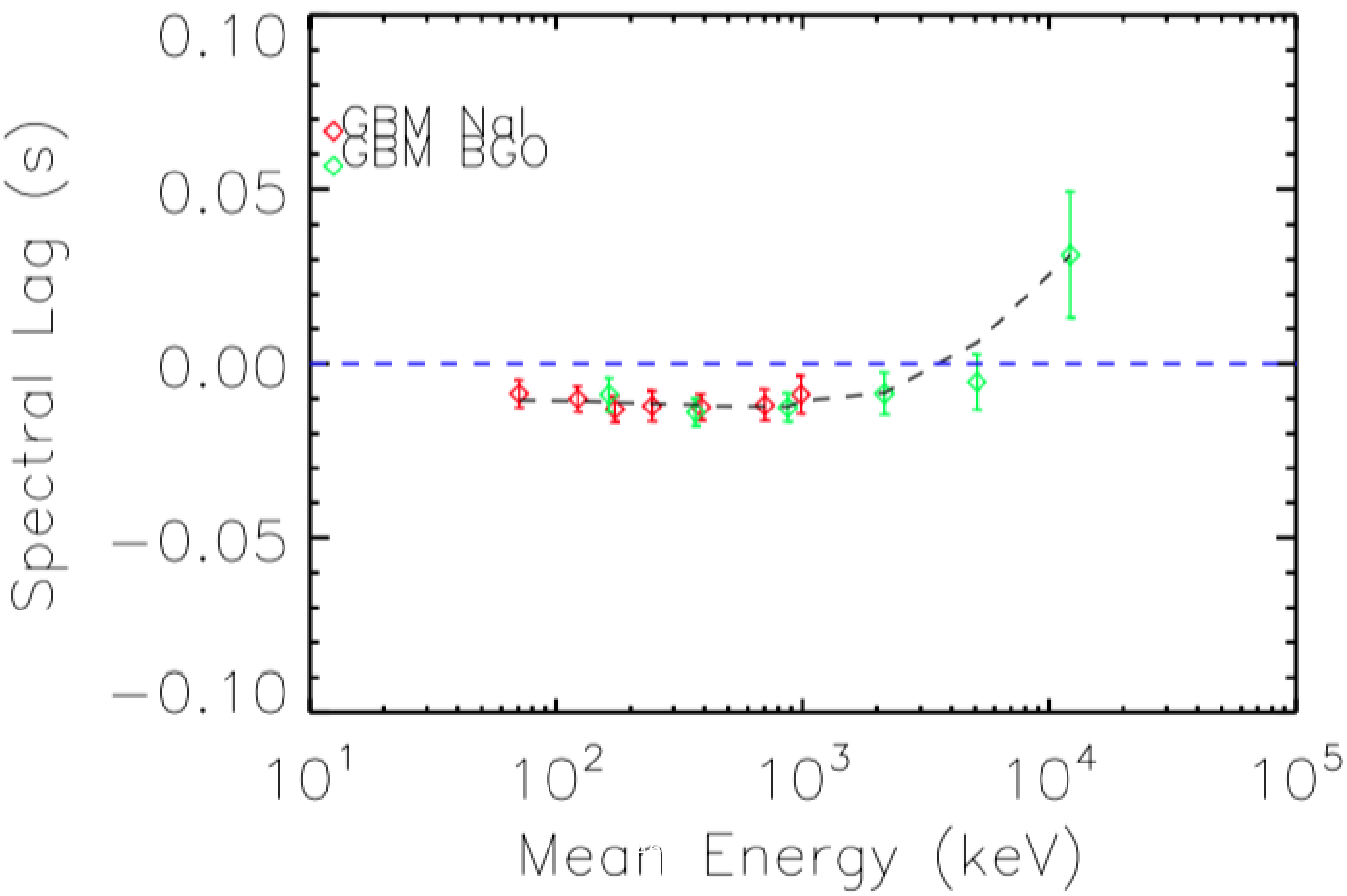
GRB130427

Exploring the Extreme Universe



Value of the time lag τ as a function of the energy band of the NaI (green dots) and BGO (blue squares) selected for the CCF analysis with the (10-100 MeV) LLE lightcurve. The dashed flux is the best fit model assuming the expected dependence of the time lag as a function of the energy.

SGRB090227772



GRB Variability Time

GRB Light curves and the role of the central engine.

According to the current Fireball model the pulses seen in γ-ray burst light curves result from collisions between shells with different values of the Lorentz factors γ;

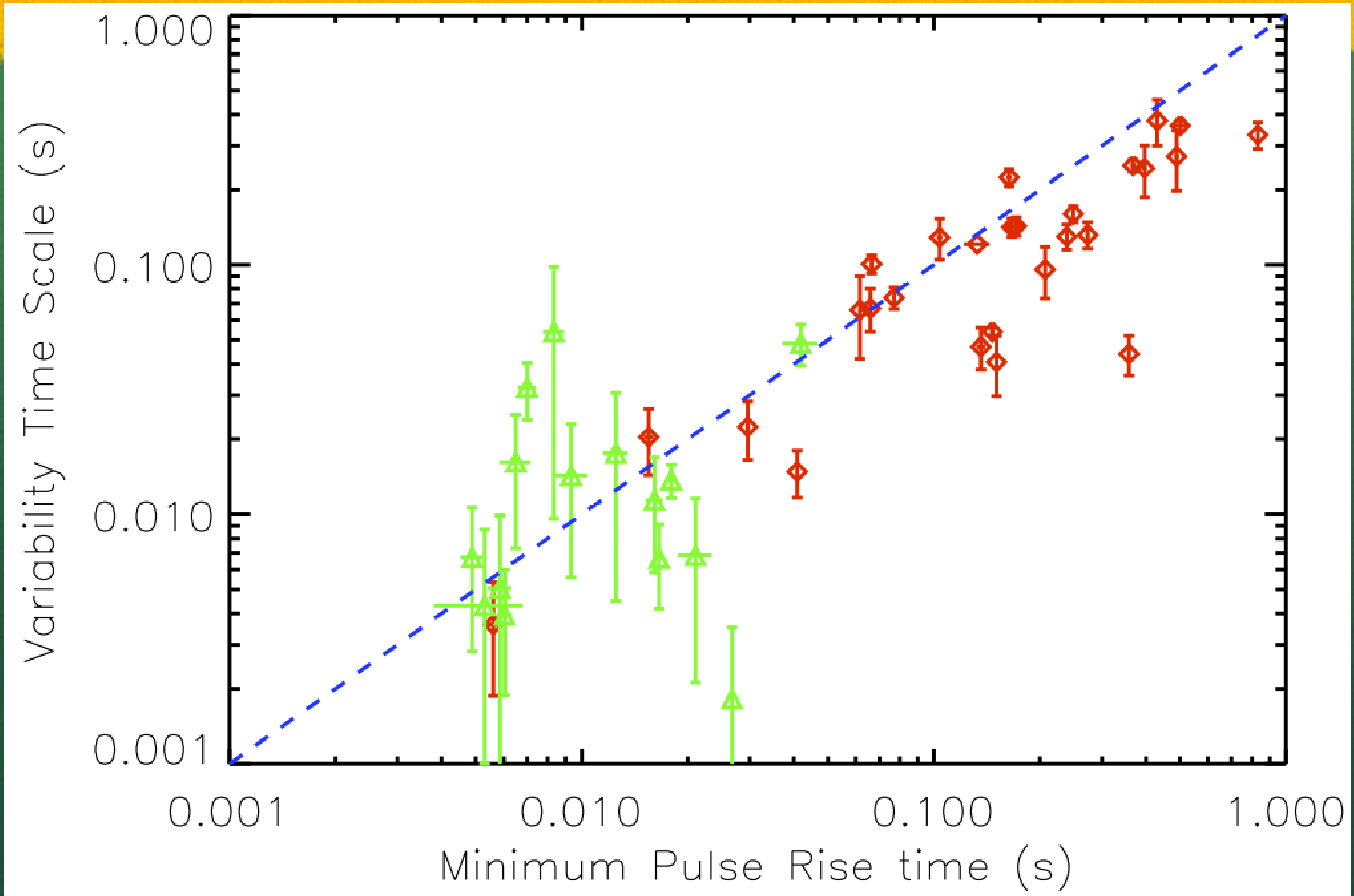
The relevant time scales that determine the pulse shape parameters are:

a. **Angular time t_{ang}, which results from the spherical geometry of the shells, $t_{ang} \sim R_c/2\Gamma^2_{sh}$**

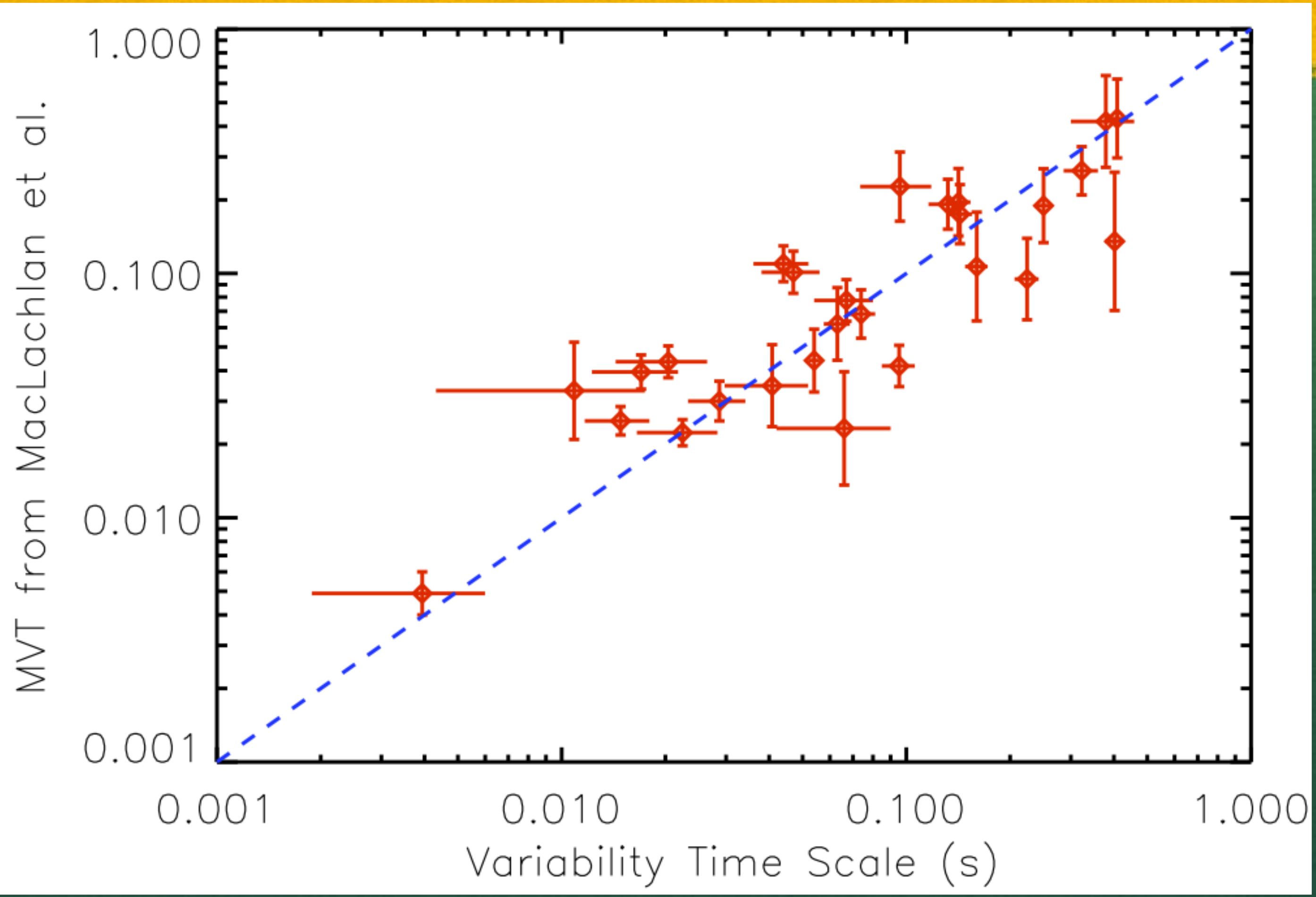
b. **The hydrodynamic time, t_{hyd}, which arises from the shell width and the shock crossing time and**

c. **The cooling time - the time that takes for the emitting electrons to cool; for synchrotron emission with typical parameters of the internal shocks, this time is much shorter than t_{ang} and t_{hyd}.**

Other factors which decide the efficiency of emission of a pulse during a collision and pulse shape are the relative Lorentz factors of the shells, the relative shell masses as well as the type of collisions.



A plot showing the optimum bin-width, t_b, of GRBs as a function the minimum rise time, t_v, of the tted lognormal pulses of the same GRB (s).



A comparison of the minimum variability times of bursts by the present method with that estimated independently by an independent method using wavelet transforms by MacLachlan et al., (2012).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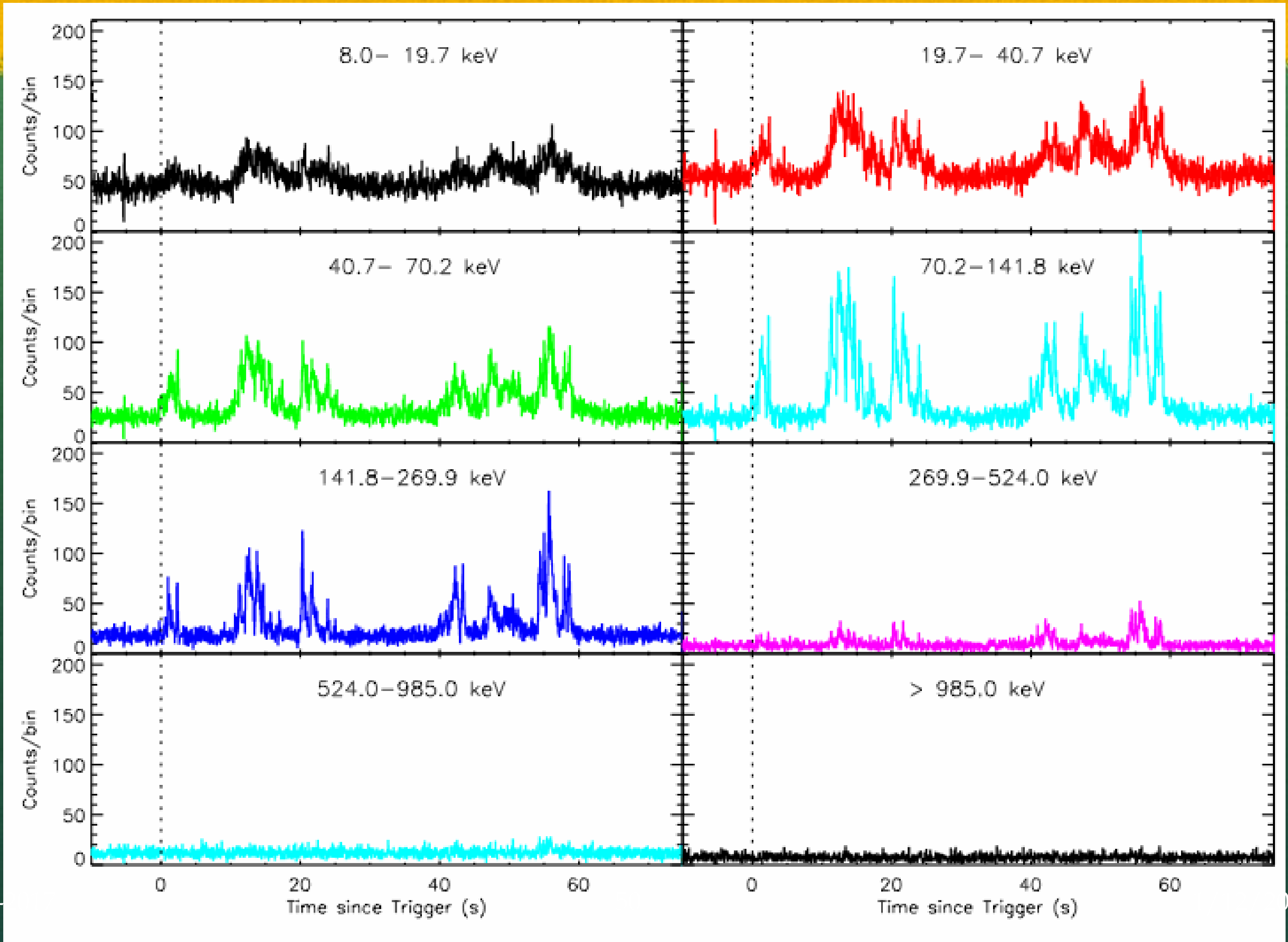
8.0– 19.7 keV
19.7– 40.7 keV
40.7– 70.2 keV
70.2–141.8 keV
141.8–269.9 keV
269.9–524.0 keV
524.0–985.0 keV
> 985.0 keV
Counts/bin
0
50
100
150
200
Time since Trigger (s)
0
20
40
60

Untargeted GBM offline searches for sGRB's

- Search algorithm for un-triggered short GRBs (sGRBs)
  - Using Ctime Tagged Event data, 2μs time resolution, 128 energy channels.
  - 2 detectors: 2.5 σ and another 1.25 σ above background
    - On-Board, 2 detectors: 4.5 ≤ σ≤ 7.5
  - 10 timescales: 0.1s to 2.8s
    - On-Board: 16 ms≤ t ≤ 8.096 s
  - 5 energy ranges (optimized on GBM-triggered weak sGRBs)
  - Unfavorable geometry of the two above-threshold detectors are eliminated
  - Soft and long duration candidates are removed

➔**Additional ~35 per year**, most of them undetected by other instruments (verification in progress)

GW150914-GBM

Fermi Gamma-ray Space Telescope

Exploring the Extreme Universe