Fermi GBM transient searches with ADWO

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GPU Day 2017

Electromagnetic transients related to the GW events

Searching for high energy electromagnetic transients with ADWO

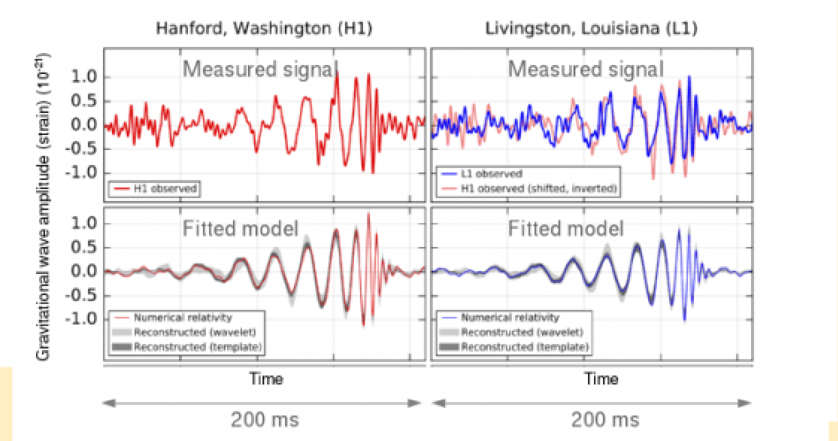
A&A 593, L10 (2016)
ZsB, István Csabai , László Dobos, Viktor L. Tóth,
János Lichtenberger (Eötvös University)
Dorottya Szécsi (Ondřejov Obs.)
István Horváth, (NUPS)
Lajos G. Balázs (Konkoly Observatory)

Fermi: Connaughton+16

OTKA NN111016, NN114560, World Wide Lightning Location Network, Wigner GPU Laboratórium.

Gravitational waves I.

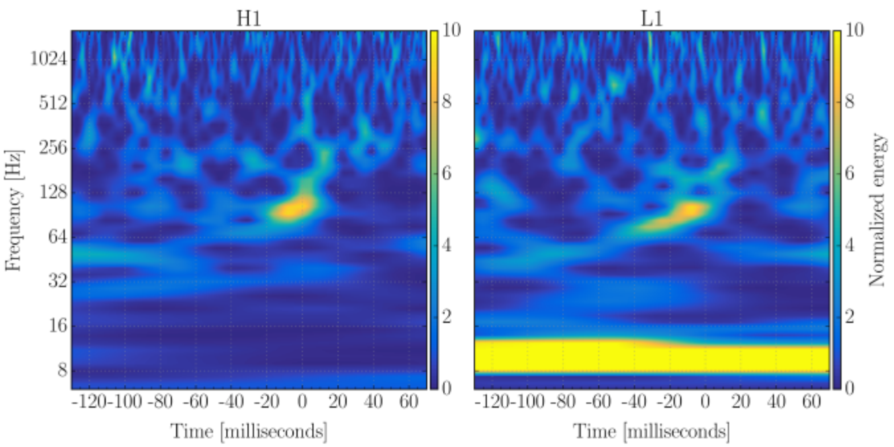
GW150914



Triggered on 14/09/2015 09:50:45.391 UTC.,
$z = 0.093(+0.030/0.036)$.

Gravitational waves II.

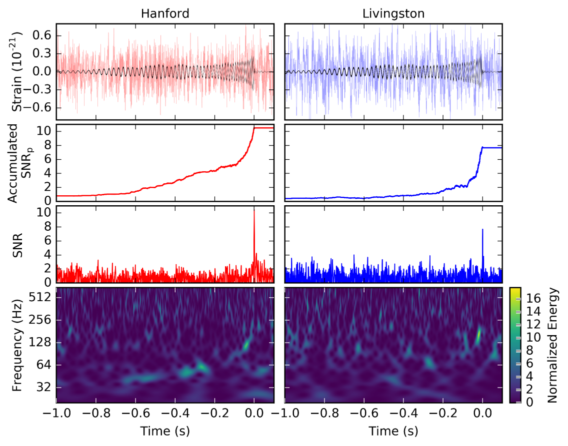
LVT151012



Triggered on 02/10/2015 09:54:43.44 UTC, $z = 0.20(+0.09/-0.09)$.

Gravitational waves III.

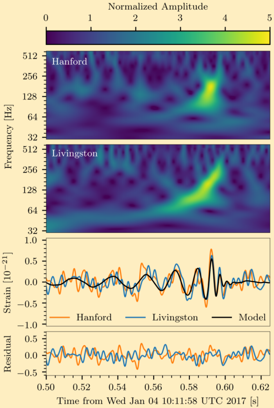
GW151226



Triggered on 26/12/2015 03:38:53.647 UTC. $z = 0.09(+0.03/-0.04)$.

Gravitational waves III.

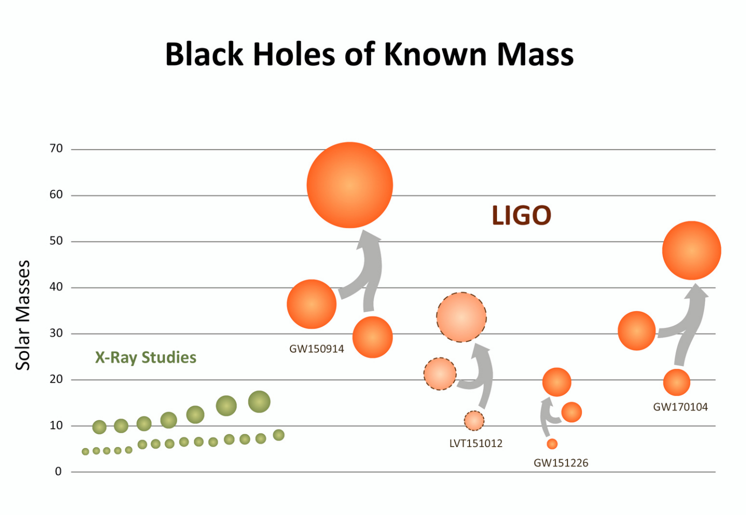
GW170104



Triggered on 04/01/2017 10:11:58.599 UTC, $z = 0.18(+/-0.08)$.

Gravitational wave sources

Mass distribution



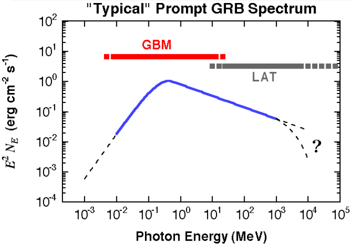
Observing EM transients

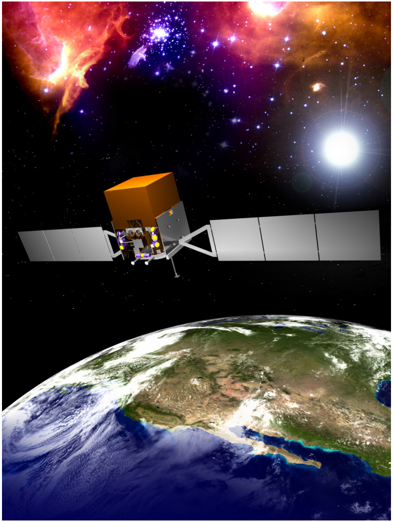
GRB satellites

- Detectors in the space: VELA, SMM, Ginga, BATSE, Ulysses, BeppoSAX, Integral, Swift, Fermi ...
- Gamma-detectors (NaI, CsI): big masses!
- International Planetary Network: position with timing
- Balloons

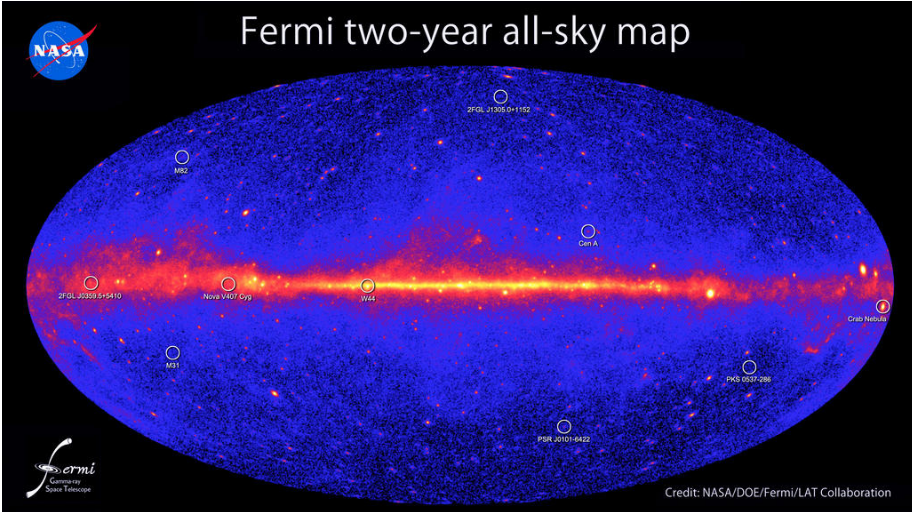
(GLAST)-Fermi (2008-)

- $\approx$ 250 GRB/year
- 10keV - GeV range!
- GBM: NaI, BGO detectors
- LAT: above $\approx$ 10 MeV
- sky survey and automatic re-pointing





Transient Fermi GeV sky

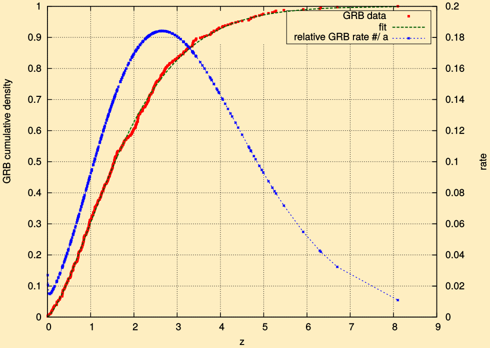


Where are the GW sources/GRBs?

Short GRB - GW source connection?

Are they the REAL GW sources? Low masses in the simulations!

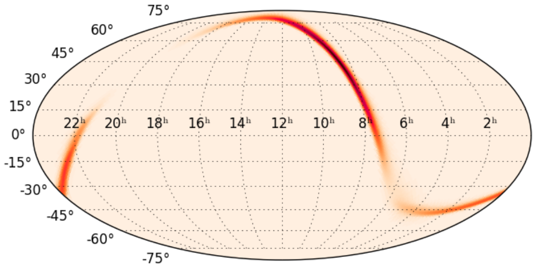
Redshift distribution (404 GRBs)



GW: observed z in the 0.09-0.2 range

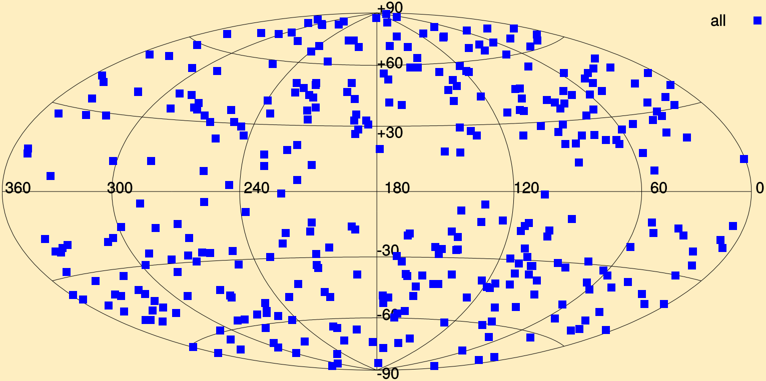
Where are the GW sources on the sky?

E.g. GW170104



Where are the GRBs on the sky?

Sky distribution of 404 GRBs with measured *z*

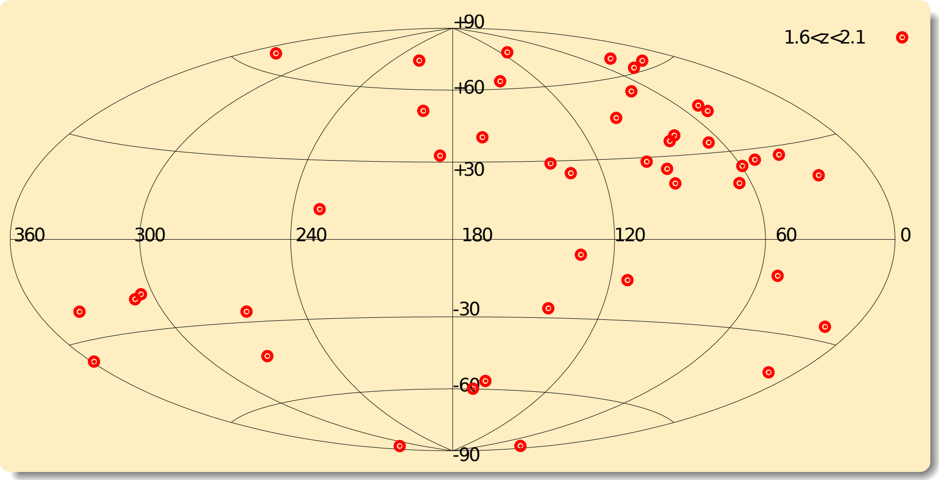


The disk of the Galaxy hinders the optical follow-up.

There's no significant difference between Northern and Southern Galactic hemispheres' *z* distribution.

Kolmogorov-Smirnov test gives 0.1155 for the p-value.

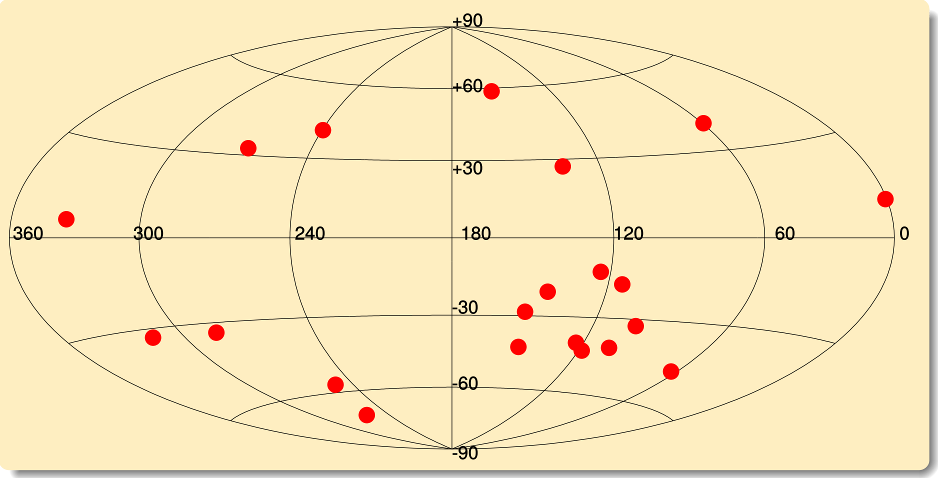
Large Gamma-ray Burst Cluster at $1.6 \leqslant z < 2.1$



Horvath+15: 8 z/distance group
Cluster in the redshift range $1.6 < z \leqslant 2.1$.

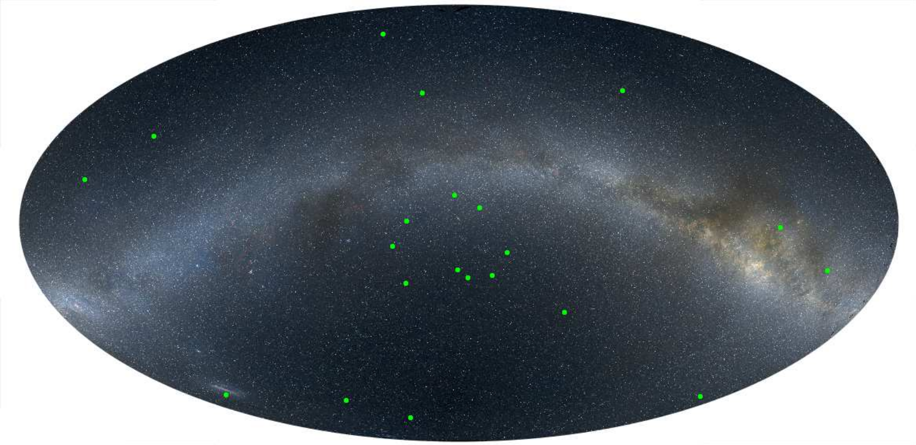
GRBs' ring-like structure at $0.78 < z < 0.86$

Balázs+16: k-th nearest neighbour distribution



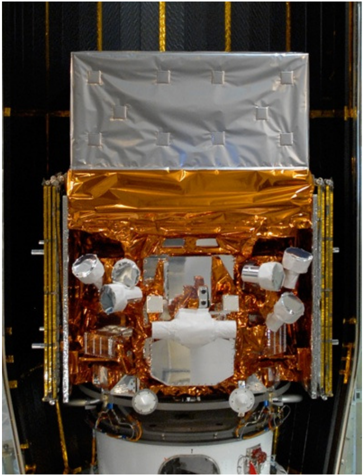
k=12, diameter of 1720 Mpc, distance of 2770 Mpc.

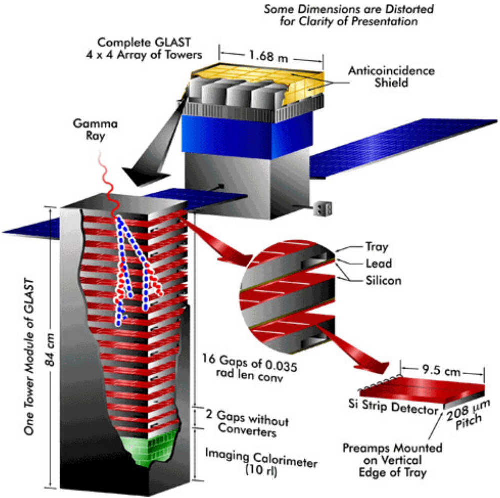
GRBs' ring-like structure at $0.78 < z < 0.86$



Can be a projection of a spheroidal structure, if each host has a period of 2.5×10^8 years during which the GRB rate is enhanced.

Fermi detectors





Fermi GBM detectors

12 NaI(Tl) detectors: 8 keV - $\sim$ 1 MeV, 2 BGO detectors: $\sim$ 200 keV - $\sim$ 40 MeV, 128 energy channels, 2μs time resolution for all detectors Continous Time Tagged Events (CTTE) since 26/11/2012.

Effective area depends on the energy and direction

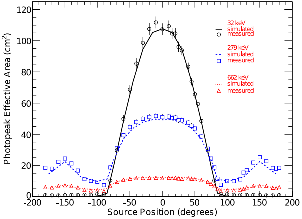


Figure 12. Angular dependence of the NaI detector effective area.

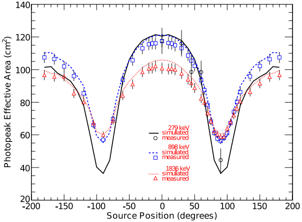


Figure 13. Angular dependence of the BGO detector effective area.

(Meegan+ 2009)

Detector Response Matrix (DRM).

Multiple triggers: # of triggered detectors, thresholds ($4.5 - 7.5\sigma$) and energy channel ($25 - 50 - 100 - 300, > 300$ keV):
$\approx$ 75 active triggers (max. 120).

GW150914 Fermi NaI sums: Connaughton+16

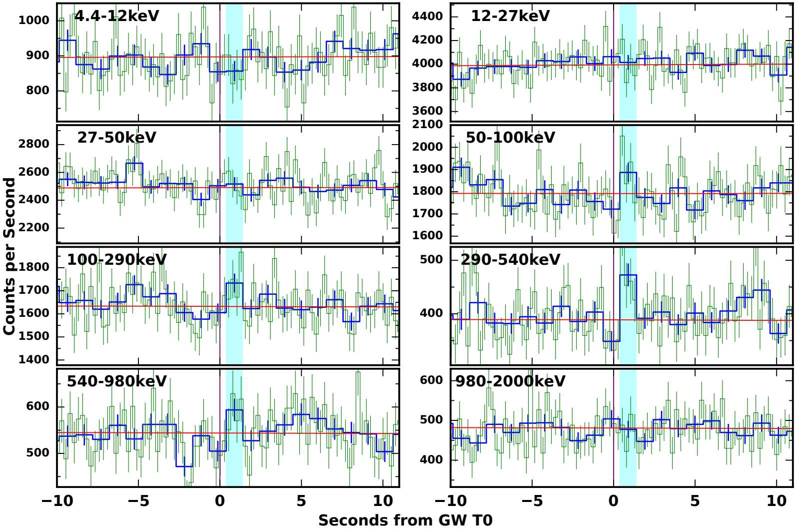


Fig. 5.— Detected count rates summed over NaI detectors in 8 energy channels, as a function of

GW150914 Fermi BGO sums: Connaughton+16

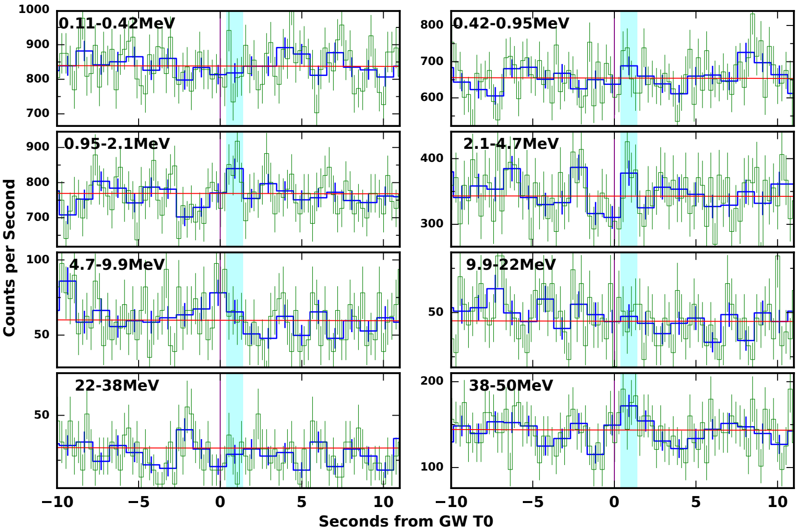


Fig. 6.— Detected count rates summed over BGO detectors in 8 energy channels, as a function of

GW150914 Fermi EM counterpart

Connaughton+16:

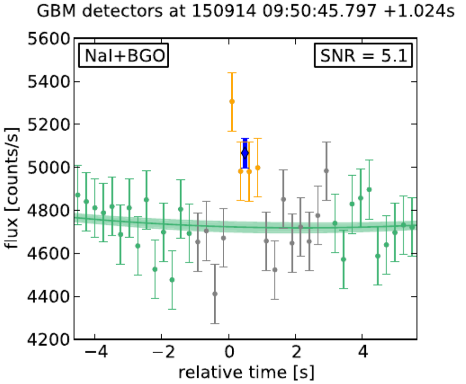


Figure 2. Model-dependent count rates detected as a function of time relative to the start of GW150914-GBM, ~0.4 s after the GW event. The raw count rates are weighted and summed to maximize the signal to noise for a modeled source. CTIME time bins are 0.256 s wide. The green data points are used in the background fit. The gold points are the counts in the time period that shows significant emission, the gray points are outside this time period, and the blue point shows the 1.024 s average over the gold points. For a single spectrum and

GW150914 Fermi EM counterpart

Energy spectra (Connaughton+16)

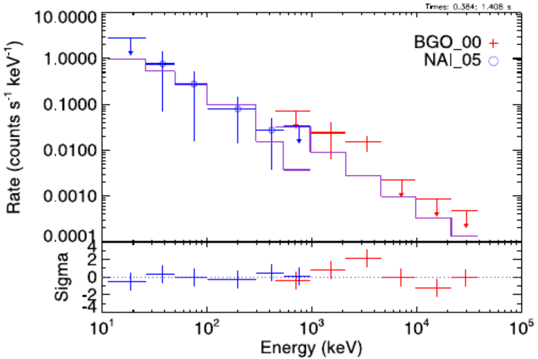


Figure 5. Power-law fit to the data from 0.384 to 1.408 s relative to the time of GW150914, from NaI 5 (blue) and BGO 0 (red), corresponding to the high time bin in Figure 7. The symbols show the data. The solid line shows the best-fit power-law model. Residuals on the bottom panel show scatter but no systematic deviation. We cannot use the first and last energy channels in either detector data type (there are threshold effects and electronic overflow events), leaving the data from 12 energy channels included in the fit.

GW150914 Fermi EM counterpart

Candidate probability (Connaughton+16)

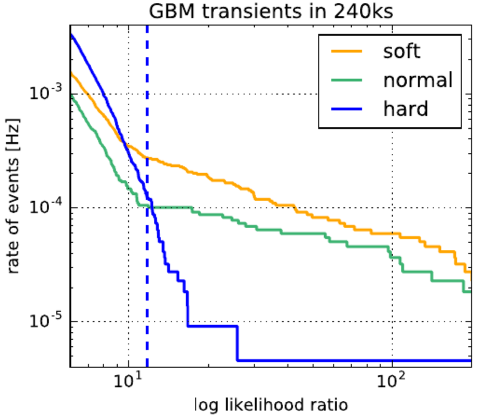


Figure 3. Distribution of transients identified by the targeted search pipeline in ±120 ks of GBM data surrounding GW150914. The events are between 0.256 and 8.192 s in duration and sorted by best-fit spectral type. The dotted blue line marks the likelihood ratio assigned to nearby candidate GW150914-GBM, while the long-tail in the blue curve (hard spectrum) represents the single on board triggered GRB in the data sample. The green and gold curves show the candidates that favor the other template spectra used in the search.

Sky position (Connaughton+16)

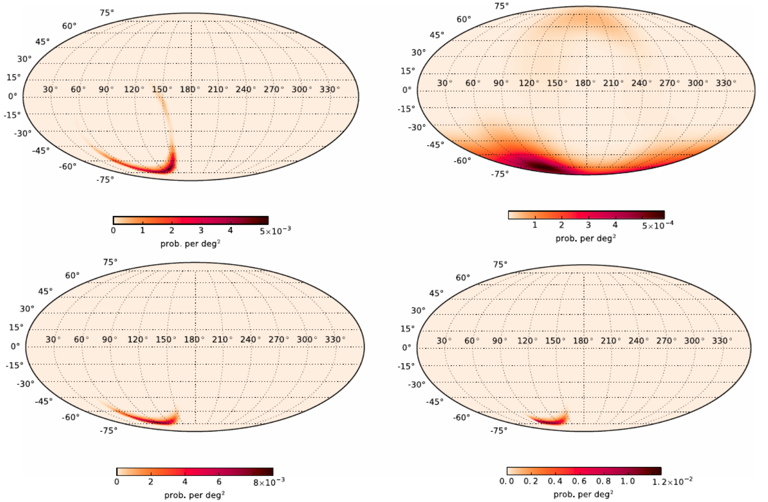


Figure 4. The LIGO localization map (top left) can be combined with the GBM localization map for GW150914-GBM (top right) assuming GW150914-GBM is associated with GW150914. The combined map is shown (bottom left) with the sky region that is occulted to *Fermi* removed in the bottom right plot. The constraint from *Fermi* shrinks the 90% confidence region for the LIGO localization from 601 to 199 square degrees.

Automatized Detector Weight Optimization (ADWO)

One signal from many detectors and energy channels - we know the approximate time.
Usual way: background modell + spectral signal with DRM, fitted with the binned data
Usually we do NOT know the DRM!

Simple solution: sum the data. Simple but NOISY!

Optimal summing: only the strong signals are needed.
Which ones are the important signals?

Non-negative weights

e_i for the energy and d_j for the detectors ($\sum e_i = 1, \sum d_j = 1$).

Automatized Detector Weight Optimization (ADWO)

Let $C_{ij}(t)$ be a background substracted intensity.
The composite signal is:

$$S(t) = \sum_{i,j} e_i d_j C_{ij}(t)$$

$S(t)$: the maximum of the signal within the search intervall
$B(t)$: the maximum outside the intervall.

Maximize $S(t)/B(t)$, the Signal's Peak to Background's Peak Ratio (SPBPR).

Matlab/Octave code, using *fminsearch*, (GitHub `https://github.com/zbagoly/ADWO`).

GPU or CPU?

GeForce GTX 750 Ti with compute capability 5.0 + CUDA 8.0

$C_{ij}(t)$		$e_i d_j$		
N1	× N2	N2	× N3	Gflop/s
32768	128	128	1	14.11
32768	128	128	2	28.19
32768	128	128	4	56.27
32768	128	128	8	112.54
32768	128	128	16	223.92
32768	128	128	32	422.57
32768	128	128	64	738.74
32768	128	128	128	1105.54
32768	128	128	256	1139.46

GPU or CPU?

Intel Core i7-4770K CPU @ 3.50GHz + octave 4.2.1 + ATLAS3.10.2

$C_{ij}(t)$		$e_i d_j$		
N1	× N2	N2	× N3	Gflop/s
32768	128	128	1	3.05
32768	128	128	2	1.57
32768	128	128	4	3.14
32768	128	128	8	6.00
32768	128	128	16	14.76
32768	128	128	32	22.92
32768	128	128	64	97.19
32768	128	128	128	109.61
32768	128	128	256	179.17

GPU or CPU?

Intel Core i7-4770K CPU @ 3.50GHz + octave 4.2.1 + ATLAS3.10.2

$C_{ij}(t)$		$e_i d_j$		
N1	× N2	N2	× N3	Gflop/s
524288	128	128	1	9.41
524288	128	128	2	1.45
524288	128	128	4	3.48
524288	128	128	8	5.56
524288	128	128	16	34.63
524288	128	128	32	49.31
524288	128	128	64	97.80
524288	128	128	128	121.19
524288	128	128	256	129.57

GPU or CPU?

octave 4.2.1 + cuBLAS 8.0

$C_{ij}(t)$		$e_i d_j$		
N1	× N2	N2	× N3	Gflop/s
524288	128	128	1	6.74
524288	128	128	2	2.02
524288	128	128	4	2.87
524288	128	128	8	7.64
524288	128	128	16	30.42
524288	128	128	32	53.01
524288	128	128	64	77.61
524288	128	128	128	114.75
524288	128	128	256	146.49

CPU is faster for 524288 × 128 × 1!

Analysis of the Fermi data

$e_1 \ldots e_8$ CTIME energy channels (according to Connaughton+16): the limits are 4.4, 12, 27, 50, 100, 290, 540, 980 and 2000 keV
Low energy channels are quite noisy $\rightarrow$ Only the 27-2000 keV range ($e_3 \ldots e_8$) are taken

All the Na(I) and BGO detectors are used, but no BGO data for $e_3 - e_4$: $6 \times 14 - 2 \times 2 = 80$ time series.

Continous Time Tagged Events (CTTE)

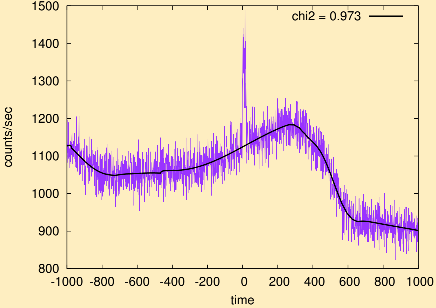
$\approx$ 5.8 ms intervall between photons in average
Smoothing with a 64ms sliding window, 11.2 photons in the window.
(What is the optimal kernel for an inhomogenous Poisson process?)

Total window: $\approx (-200, 500)$ s around the event, approx. 1/7 orbit.

Fermi background fit

Szécsi+13: sky+geometry+directions with pseudoinverse

E.g: GRB091030613 background:

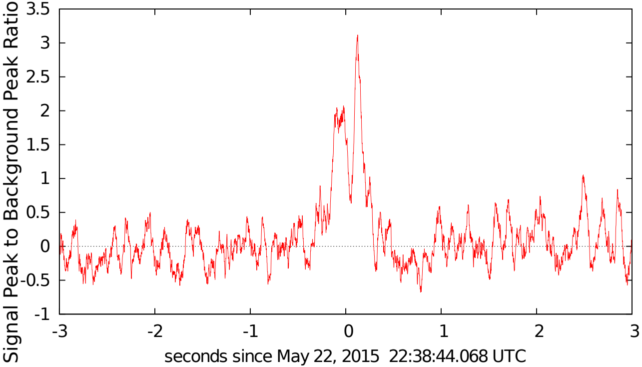


Here: short signals only, 6^{th} order polynome background (like Connaughton+16).

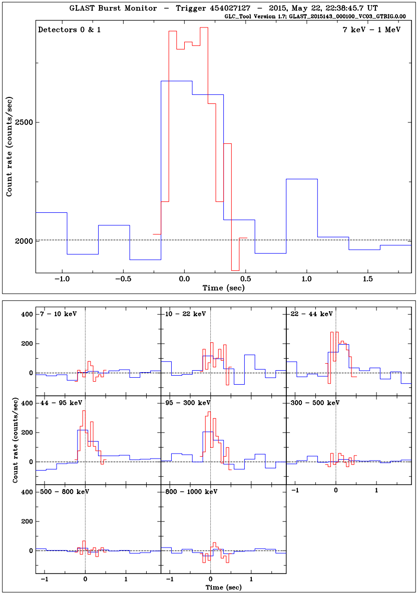
GRB150522B

22/05/2015 22:38:44.068 UTC.
$T_{90} = 1.02 \pm\ 0.58$s , fluence=$2.13 \pm\ 0.12 \times 10^{-7}$erg/cm^2
(selected to be similar to the GW150914 EM event)

ADWO: SPBPR=3.12



GRB150522B: Fermi quicklook data



GRB150522B: significance

10^4 Monte-Carlo (MC) simulations using the background

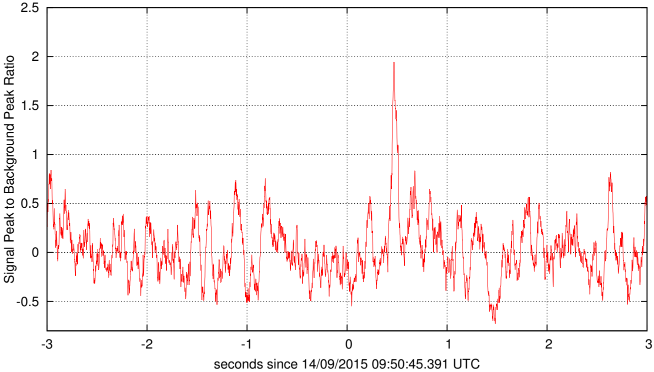
There was no case with SPBPR> 3.12:

2×10^{-5} Hz the error rate

The probability is
2×10^{-5} Hz $\times$ 0.125 s $\times$ $(1 + \ln(6\ \text{s}/64\ \text{ms})) = 2.8 \times 10^{-5}$

GW150914

$(-195, 495)$s window around 14/09/2015 09:50:45 UTC (391ms before trigger).
ADWO: maximum is SPBPR=1.911, 474 ms after the GW trigger (no time constraint for ADWO!).



GW150914 Fermi EM counterpart

Connaughton+16:

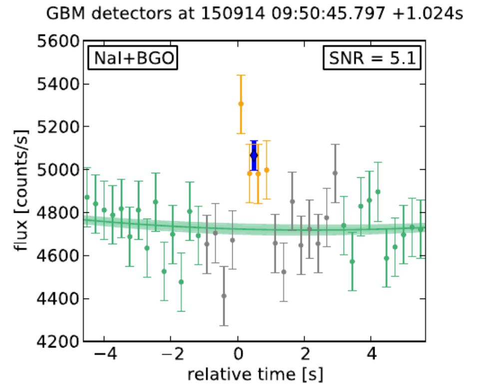


Figure 2. Model-dependent count rates detected as a function of time relative to the start of GW150914-GBM, ~0.4 s after the GW event. The raw count rates are weighted and summed to maximize the signal to noise for a modeled source. CTIME time bins are 0.256 s wide. The green data points are used in the background fit. The gold points are the counts in the time period that shows significant emission, the gray points are outside this time period, and the blue point shows the 1.024 s average over the gold points. For a single spectrum and

GW150914: significance

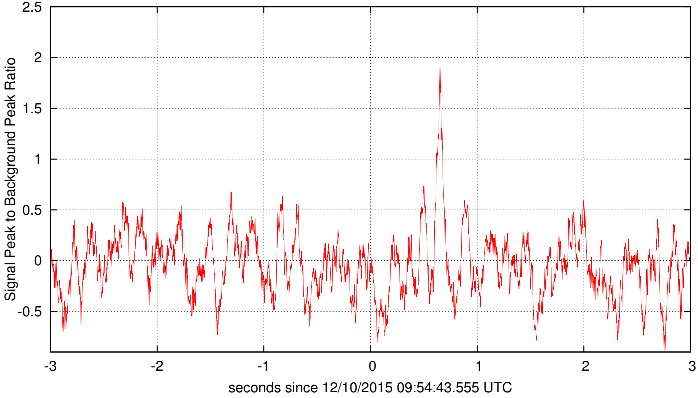
10^4 Monte-Carlo (MC) simulation, 86 cases with SPBPR>1.911.

0.0014 Hz rate of the error

The probability is
2.8×10^{-3} Hz $\times$ 0.474 s $\times$ $(1 + \ln(6\text{ s}/64\text{ ms})) = 0.0075$.
(Connaughton+16: 0.0022)

LVT151012

$(-195, 495)$s intervall around 02/10/2015 09:54:43.44 UTC
ADWO: maximum is SPBPR=1.805, 652 ms later.



LVT151012: significance

10^4 Monte-Carlo (MC) simulations, 308 cases with SPBPR>1.805.

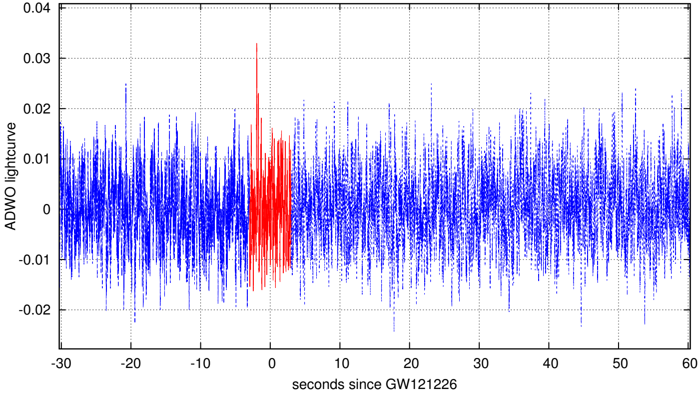
Error rate is 0.0051 Hz.

The probability is 0.01 Hz $\times$ 0.652 s $\times$ $(1 + \ln(6\ \mathrm{s}/64\ \mathrm{ms})) = 0.037$.

No lighning/TGF.

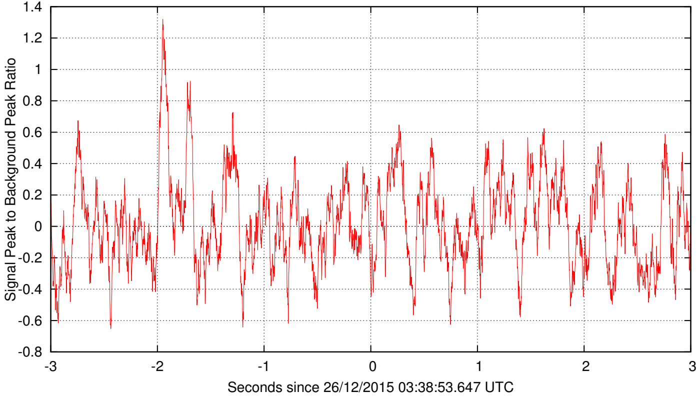
GW121226

Triggered on 26/12/2015 03:38:53.647 UTC.
ADWO: maximum is SPBPR=1.321, probably noise.



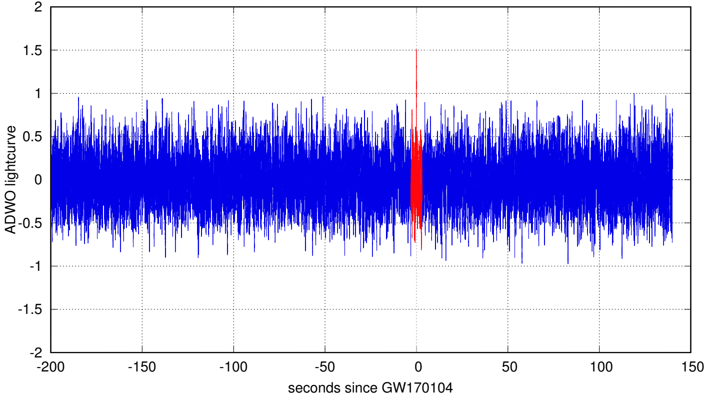
GW121226

Triggered on 26/12/2015 03:38:53.647 UTC.
ADWO: maximum is SPBPR=1.321, probably noise.



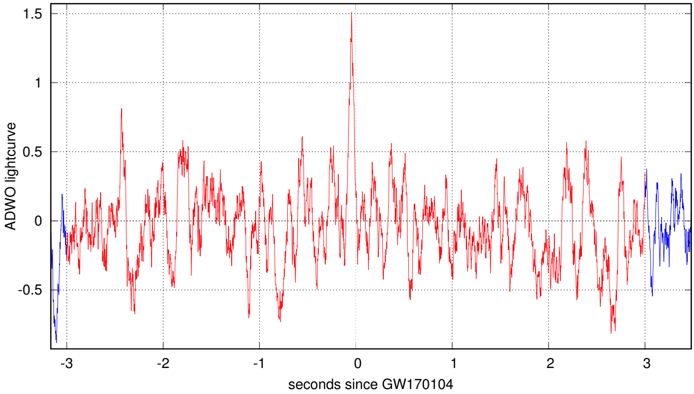
GW170104

$(-200, 140)$s intervall around 04/01/2017 10:11:58.599 UTC.
ADWO: maximum is SPBPR=1.51, probably noise.



GW170104

Triggered on 04/01/2017 10:11:58.599 UTC.
ADWO: maximum is SPBPR=1.51, at $T \approx -50$ms, probably noise.

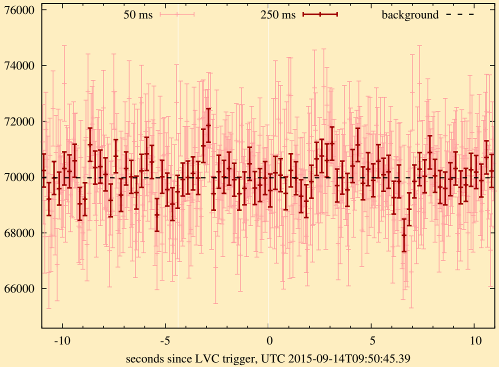


GW150914 other observations

Swift (Evans+16): no prompt signal

Rhessi BGO data + ADWO: no signal (Ripa+17)

GW150914, Savchenko+16, Integral: no signal



GW150914 other analysis

Greiner+16: No signal in the Fermi data

Uses only a few from the 14 detectors!

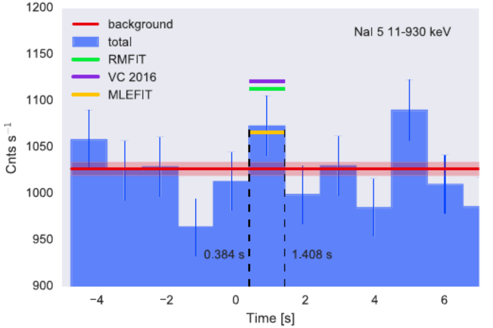


Figure 5. Total, raw count light curve of NaI 5 (blue) integrated over 11–930 keV. The modeled background (red) with shaded 1σ Gaussian error is shown in red. Using the GBM DRM, we calculate the predicted counts from power-law fits using our method (yellow), our fit with RMFIT (green), and the parameters reported in Connaughton et al. (2016). Both methods that rely on RMFIT overpredict the expected counts. Additionally, it is easy to see that there are spikes in the raw light curve that are equally as bright as the alleged event.

GW150914 other analysis

Greiner+16: No signal in the Fermi data

Simply sum the data from the 14 detectors for energy spectrum!

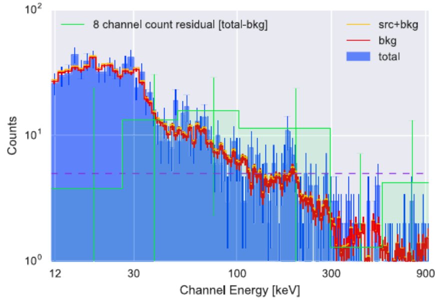
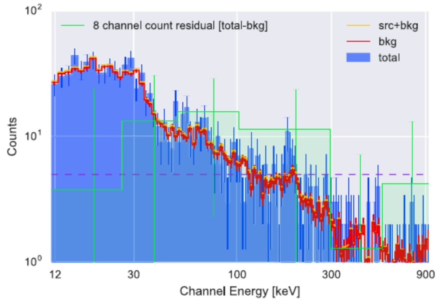


Figure 1. Spectral distribution of counts for the GBM event between 0.384 and 1.402 s in NaI 5. Shown are the total raw counts (blue), the background model from our fitted polynomial (red), the background plus source model (yellow) using the spectral parameters from our fit, and the residual source counts (green) rebinned into exactly the 8-channel spectrum as used in Connaughton et al. (2016), with the lowest (4–8 keV) and highest (overflow, i.e., >1 MeV) channel omitted. The highest-count channel is the one at 50–100 keV with 13 counts, demonstrating the low-count regime of the spectrum. The purple dashed line indicates the level at which the χ^2 background fitting method breaks down. The blue and green error bars show the Skellam (1946) confidence intervals.

GW150914 other analysis

Greiner+16: No signal in the Fermi data

Simply sum the data from the 14 detectors for energy spectrum!



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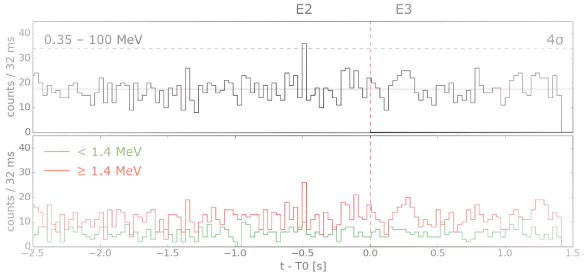
GW170104 EM observations

AGILE: weak signals, stronges at $T = -0.46s$, above 1.4 MeV



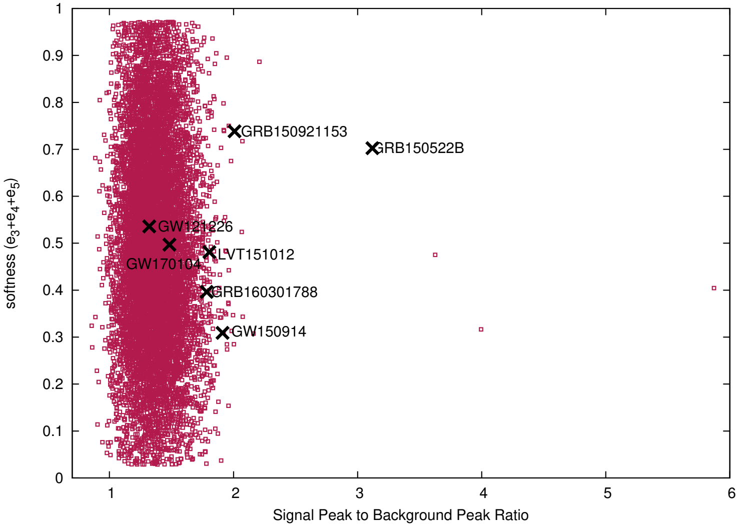
post-trial probability of 3.4σ

Fermi: no signal

AstroSat-CZTI and GROWTH: no hard EM detection, but an optical transient 23 hours later - GRB170105A ?
ATLAS and Pan-STARRS: same optical transient detected.

GW150914: investigation of the daily background

61.4 ks CTTE data, same day, no re-pointing.



$27 - 290$ keV weights for the 61.4 ks CTTE data (GW150914)

30 events with SPBPR>1.911, therefore the error rate is 4.885×10^{-4} Hz, and the probability is $2 \times 4.88 \times 10^{-4}$ Hz $\times$ 0.4 s $\times$ $(1 + \ln(6\ \text{s}/64\ \text{ms})) = 0.00216$. Smaller than 0.0075!

What is background and what is not?

ADWO search for untriggered GRBs

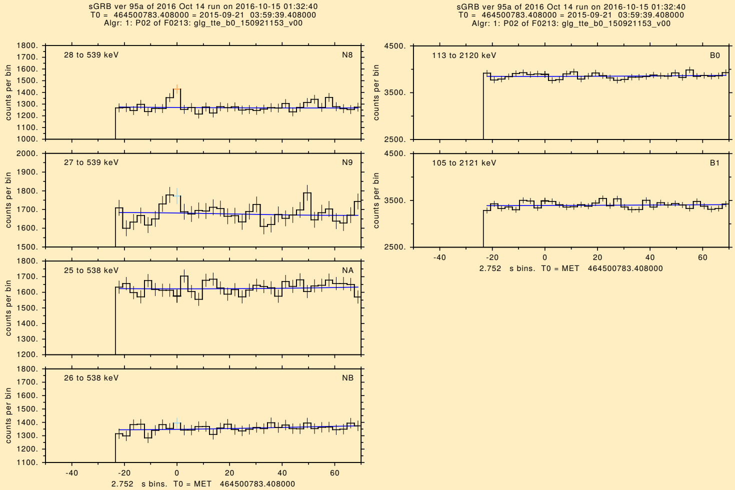
Fermi product (webpage):
offline (ground based) processing pipeline
CTIME data

ADWO search:
using CTTE data (since November 2012)
more detail/information
$\approx$ real time
event analysis can't be fully automatic (or pseudo-AI is needed)

Re-analysis of the Fermi untriggered list

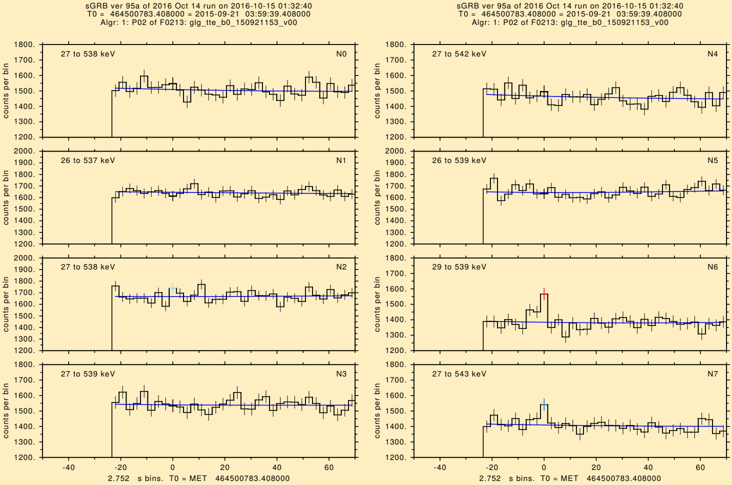
Untriggered GRB464500783

Fermi product: offline processing pipeline, CTIME data



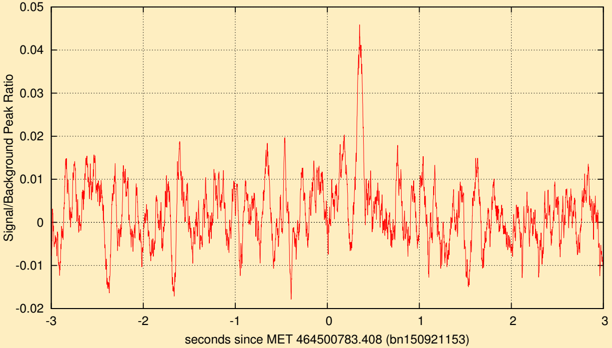
Untriggered GRB464500783

Fermi product: offline processing pipeline, CTIME data



Untriggered GRB464500783

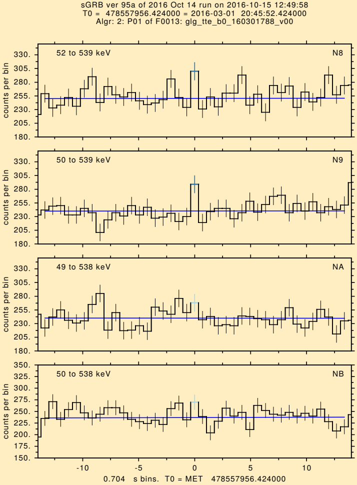
ADWO CTTE quicklook

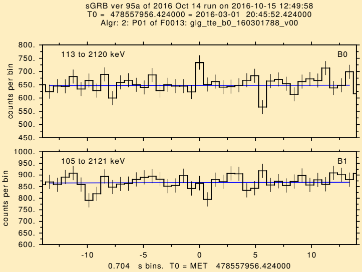


SPBPR=1.784

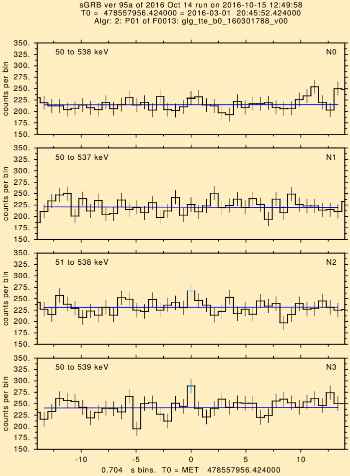
Untriggered GRB478557956

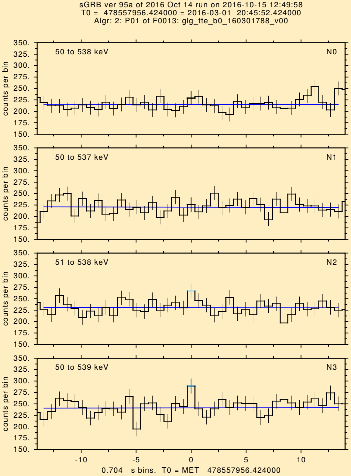
Fermi CTIME quicklook





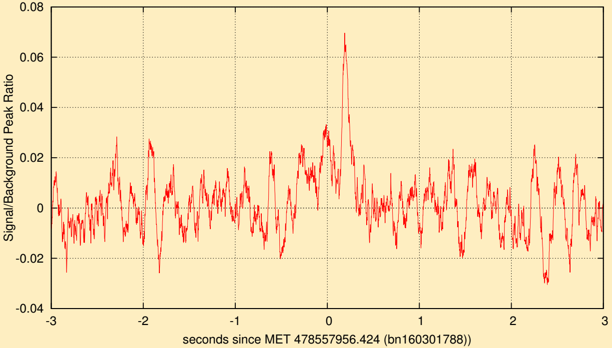
Fermi CTIME quicklook





Untriggered GRB478557956

ADWO CTTE quicklook



SPBPR=2.008

ADWO

Efficient method looking for transients.

GW EM counterparts and non-triggered (s)GRBs identification

Method impovements: optimal filter/kernel, optimalized channel selection (S/N maximalization), direction determination, multi-satellite data

More GW events are needed!

More GW events are needed!