Searching for high energy electromagnetic transients with ADWO

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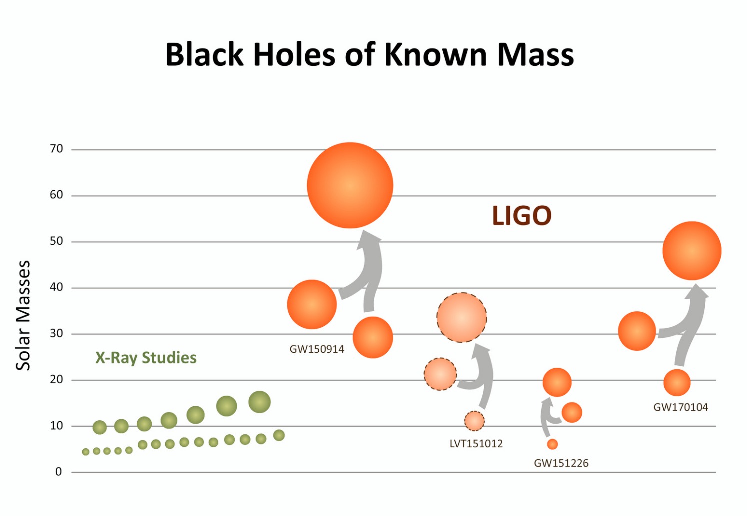
Gravitational waves

Observed events

ID	Trigger time (UTC)	redshift
GW150914	14/09/2015 09:50:45.391	0.093 $(+0.030/0.036)$
LVT151012	02/10/2015 09:54:43.440	0.20 $(+0.09/-0.09)$
GW151226	26/12/2015 03:38:53.647	0.09 $(+0.03/-0.04)$
GW170104	04/01/2017 10:11:58.599	0.18 $(+/-0.08)$

Gravitational waves

Source mass distribution



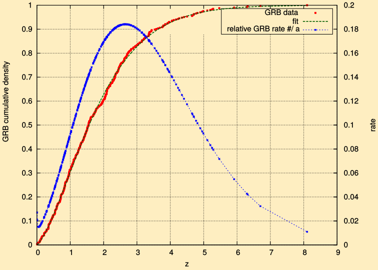
GW-GRB connection?

Short GRB - GW source connection?

Very high masses observed! Earlier models: NS+NS and BH+NS, low masses!
Szécsi's talk: current GW source models

Where are the GW sources/GRBs?

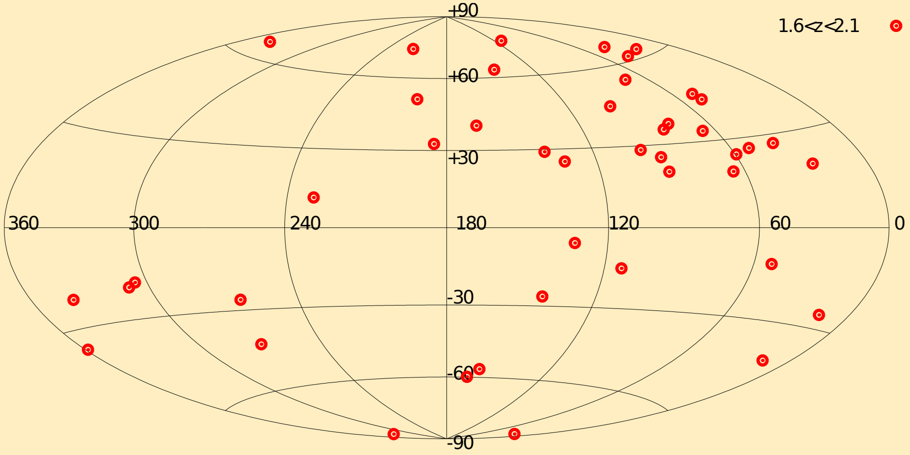
Redshift distribution (404 GRBs)



GW sources: z in the 0.09-0.2 range!

Where are the GW/GRB sources on the sky?

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

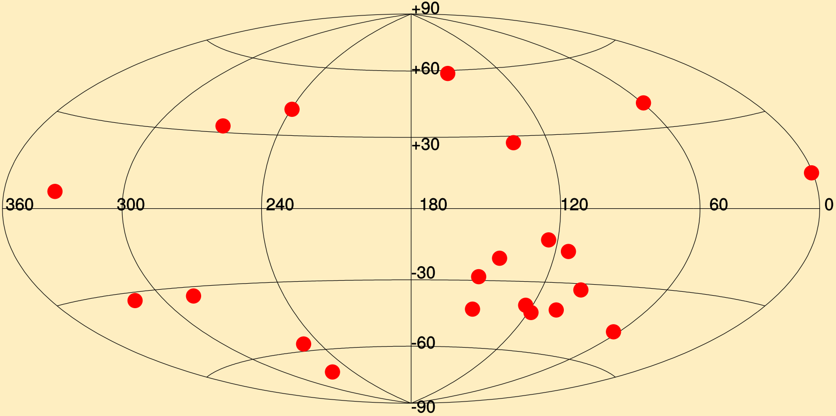


Large cluster in the redshift range $1.6 < z \leqslant 2.1$ (Horvath+15)

Where are the GRBs on the sky?

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

$k = 12$-th nearest neighbour distribution (Balázs+16)



Diameter of 1720 Mpc, distance of 2770 Mpc. Could be a spheroidal structure with enhance GRB production for 2.5×10^8 years.

Where are the GRBs on the sky?

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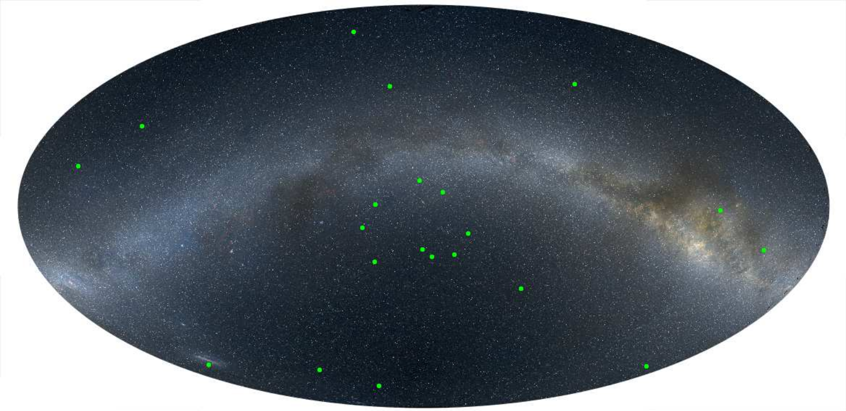
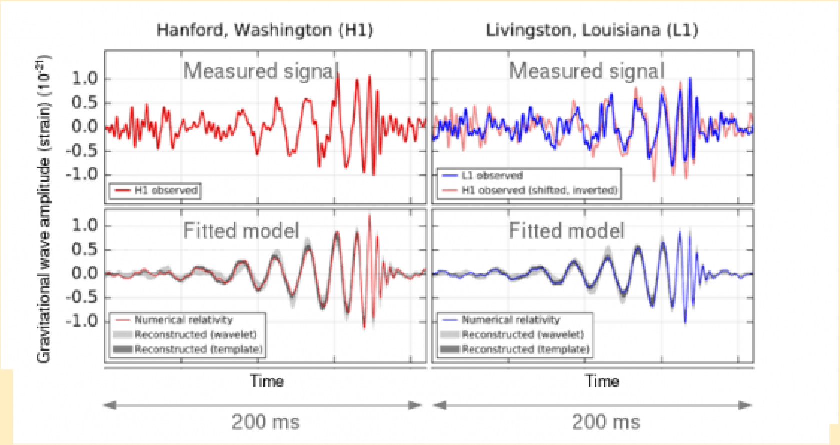


Diameter of 1720 Mpc, distance of 2770 Mpc. Could be a spheroidal structure with enhance GRB production for 2.5×10^8 years.

GW150914



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

Electromagnetic transients related to the GW events

GW150914: Fermi counterpart (Connaughton+16)

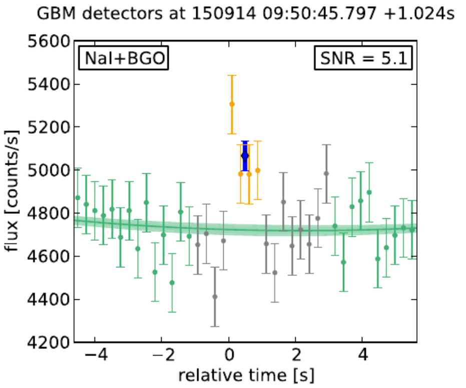


Figure 2. Model-dependent count rates detected as a function of time relative to the start of GW150914-GBM, ~0.4 s after the GW event. The raw count rates are weighted and summed to maximize the signal to noise for a modeled source. CTIME time bins are 0.256 s wide. The green data points are used in 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)

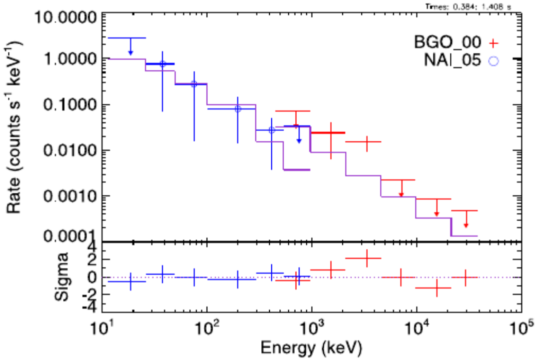


Figure 5. Power-law fit to the data from 0.384 to 1.408 s relative to the time of GW150914, from NaI 5 (blue) and BGO 0 (red), corresponding to the high time bin in Figure 7. The symbols show the data. The solid line shows the best-fit power-law model. Residuals on the bottom panel show scatter but no 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 NaI sums: Connaughton+16

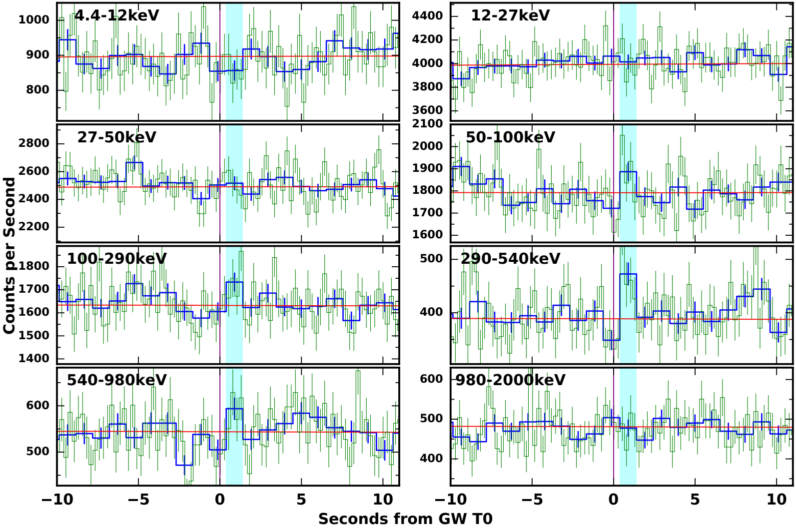


Fig. 5.— Detected count rates summed over NaI detectors in 8 energy channels, as a function of time relative to the start of the GW event GW150914. Shading highlights the interval containing

GW150914 Fermi BGO sums: Connaughton+16

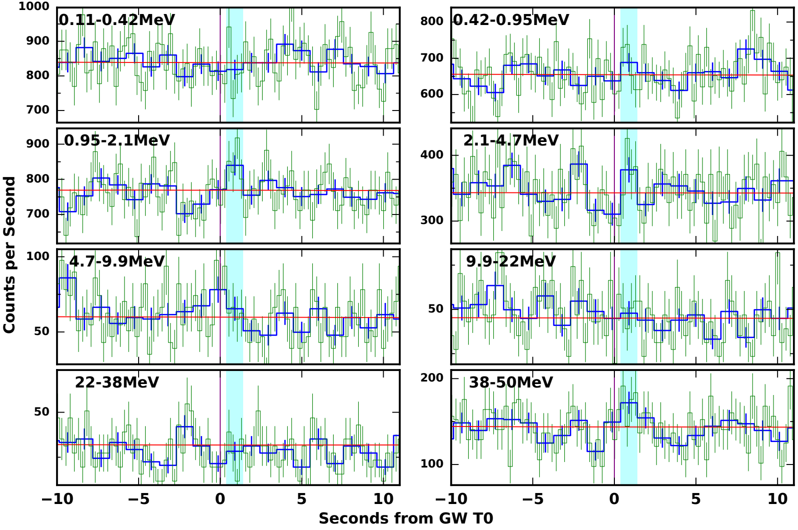


Fig. 6.— Detected count rates summed over BGO detectors in 8 energy channels, as a function of time relative to the start of the GW event GW150914. Shading highlights the interval containing

GW150914 Fermi EM counterpart

Sky position (Connaughton+16)

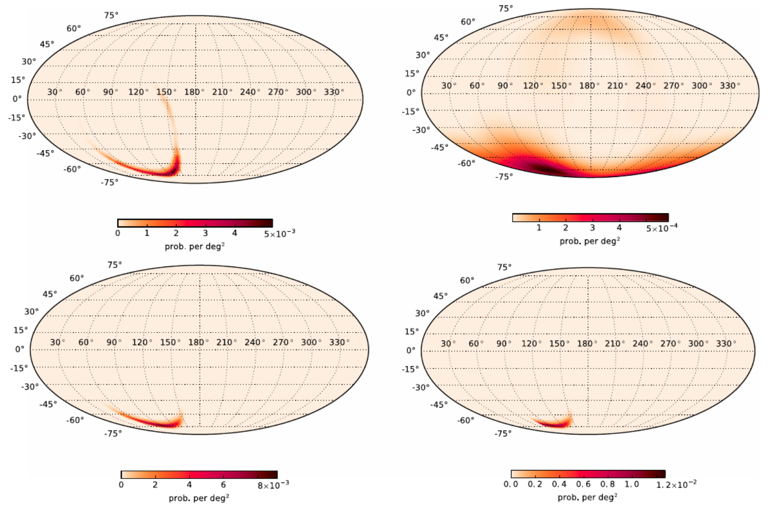


Figure 4. The LIGO localization map (top left) can be combined with the GBM localization map for GW150914-GBM (top right) assuming GW150914-GBM is associated with GW150914. The combined map is shown (bottom left) with the sky region that is occulted to *Fermi* removed in the bottom right plot. The constraint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

GW150914 observations

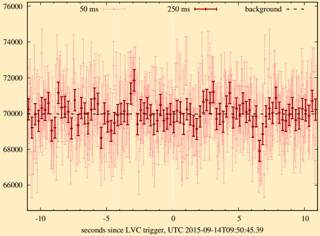
Swift (Evans+16)

No prompt signal, $>$ 50 hours later

Auger (Aab+17)

No signal

Integral SPI ACS (Savchenko+16, Pozanenko's talk)



No signal.

GW150914 Fermi re-analysis

Greiner+16: No signal in the Fermi data

Spectral simulations, but uses only a few from the 14 detectors!

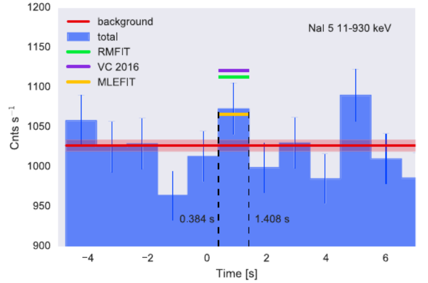


Figure 5. Total, raw count light curve of NaI 5 (blue) integrated over 11–930 keV. The modeled background (red) with shaded 1σ Gaussian error is shown in red. Using the GBM DRM, we calculate the predicted counts from power-law fits using our method (yellow), our fit with RMFIT (green), and the parameters 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.

Fermi GBM detectors

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

Effective area depends on the energy and direction

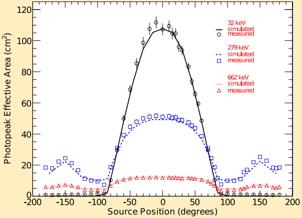


Figure 12. Angular dependence of the NaI detector effective area.

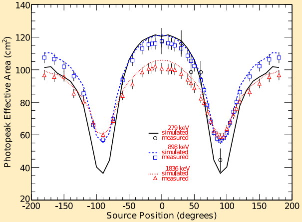


Figure 13. Angular dependence of the BGO detector effective area.
(Meegan+ 2009)

Detector Response Matrix (DRM) transforms the spectrum into counts.

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

Automatized Detector Weight Optimization (ADWO)

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

A&A 593, L10 (2016)
Acknowledgements: OTKA NN111016, NN114560, World Wide Lightning Location Network, Wigner GPU Laboratory

Automatized Detector Weight Optimization (ADWO)

The approximate trigger time is known: one signal from many detectors and energy channels.
Usually: background modell + spectral signal with DRM, fitted with the binned data.
But: we do NOT know the direction/DRM!

Naïve solution: sum the data. Simple but NOISY!

Optimal summing

Only the strong signals/detectors/channels should be added. Which ones are important?
Non-negative weights: e_i for the energy and d_j for the detectors ($\sum e_i = 1, \sum d_j = 1$).

Signal's Peak to Background's Peak Ratio

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 interval
$B(t)$: the maximum outside the interval.

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

Nonlinear optimalization.

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

Analysis of the Fermi data

Energy channels

$e_1 \ldots e_8$: 8 CTIME energy channels (128 CTTE channels summed up)

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

No BGO data for $e_3 - e_4$: $6 \times 14 - 2 \times 2 = 80$ time series.

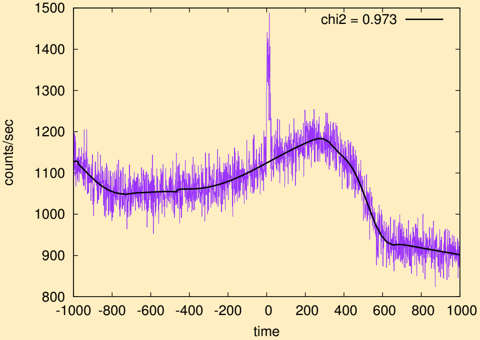
CTTE Filtering

Average $\approx$ 5.8 ms between photons in channels (at GW150914)
Smoothing with a 64ms sliding window, 11.2 photons in the window.
(Q: 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

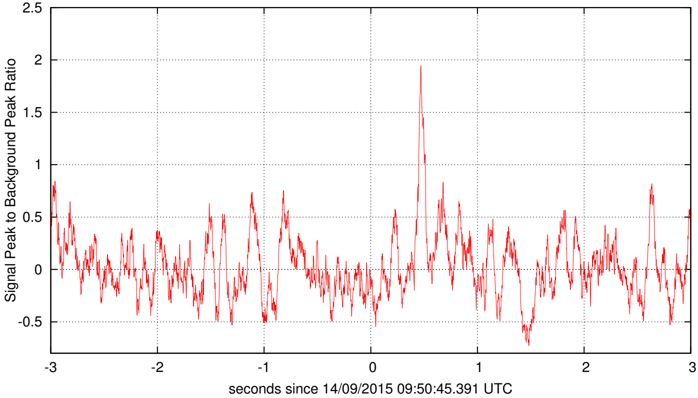
Szécsi+13: sky sources + geometry + directions with pseudoinverse
E.g: GRB091030613 background:



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

GW150914: ADWO

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



GW150914 Fermi EM counterpart

Connaughton+16:

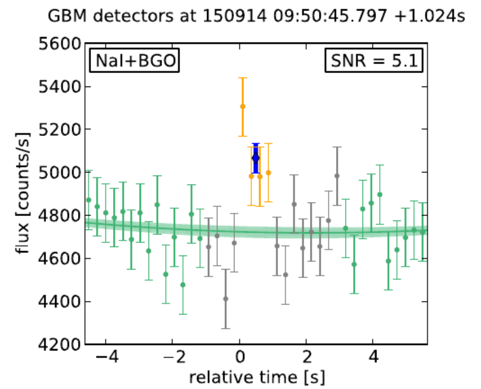


Figure 2. Model-dependent count rates detected as a function of time relative to the start of GW150914-GBM, ~0.4 s after the GW event. The raw count rates are weighted and summed to maximize the signal to noise for a modeled source. CTIME time bins are 0.256 s wide. The green data points are used in 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: ADWO significance

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

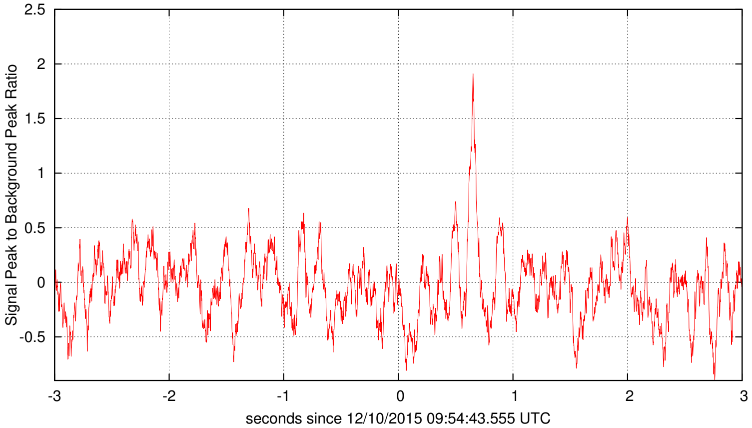
0.0014 Hz rate of the error

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

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

LVT151012: ADWO

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



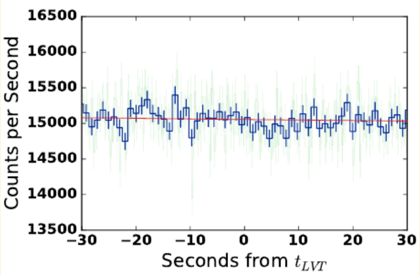
LVT151012

ADWO 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 $\times$ $(1 + \ln(6\text{ s}/64\text{ ms})) = 0.037$. No lighning/TGF.

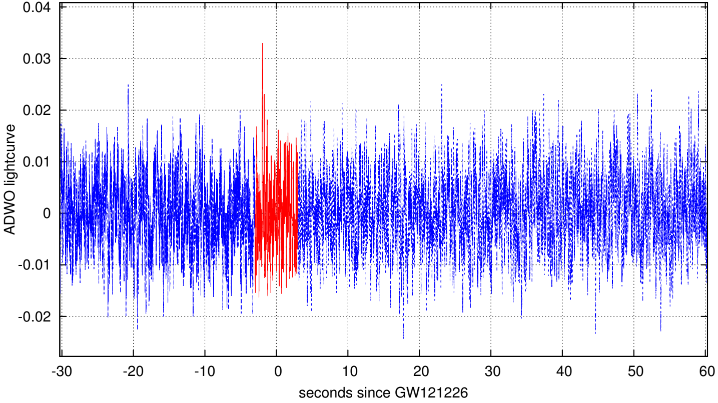
Fermi group (Racusin+16)

No signal detected



GW121226; ADWO

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



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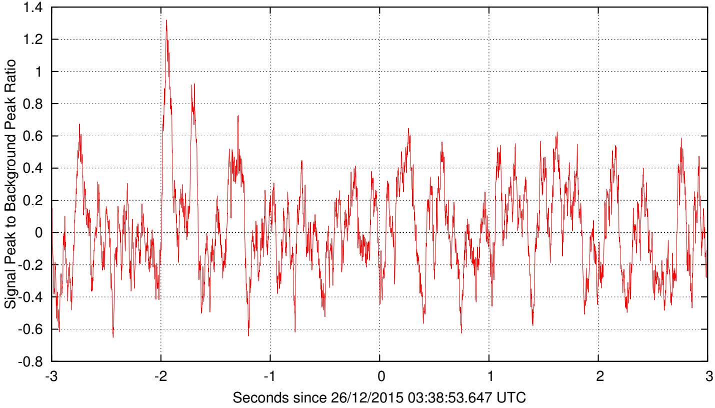
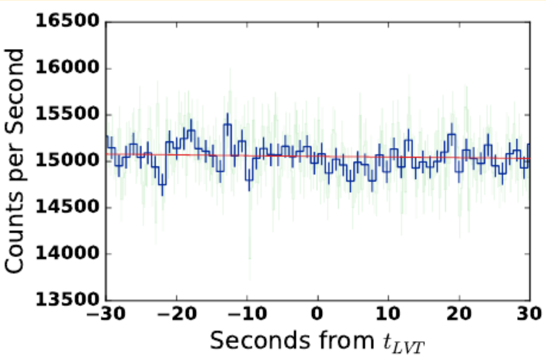


GW121226

Fermi group (Racusin+16)

No signal detected



Auger (Aab+17)

No signal

Good GBM exposure ($\approx$ 82.4%) :

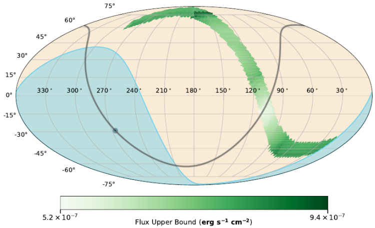


Figure 1. The 1 s flux upper bound by GBM covering the 99% credible region of the LIGO sky map. The Earth occultation

GBM upper limit: $(5.2 - 9.4) \times 10^{-7}$erg cm$^{-2}s^{-1}$ (10-1000 keV)
LAT upper limit: $(0.2 - 13) \times 10^{-9}$erg cm$^{-2}s^{-1}$ (0.1-1 GeV)

GBM most significant candidate: 5.4 s before the T_0, false alarm rate of $\approx$ 0.003 Hz.
Longer term structure for tens of seconds in the low energy channels around T_0.

GW170104 EM observations: AGILE (Verrecchia+17)

Good exposure ($\approx 36\%$) around T_0:

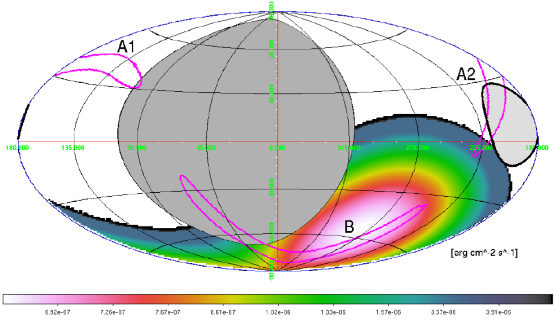


Fig. 1.— AGILE-GRID sensitivity map (in $\mathrm{erg cm^{-2} s^{-1}}$) in Galactic coordinates based on the gamma-ray exposure at the detection time T_0 of GW170104. The shadowed areas show

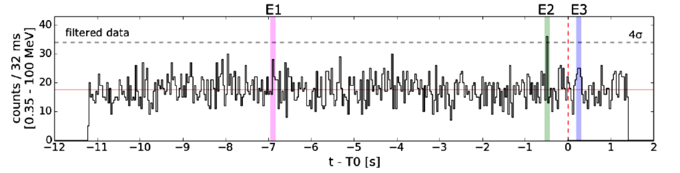
SA detector

No gamma-ray transient near T_0 over timescales of 2, 20 and 200 seconds.
Upper limit: $(1.5 - 6.6) \times 10^{-8}$erg cm^{-2} (depending on the direction)

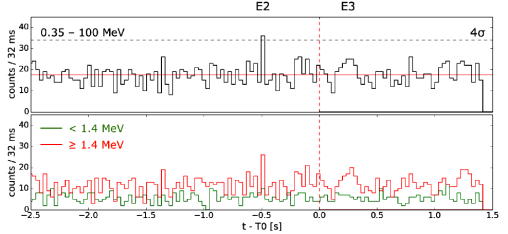
GW170104 EM observations: AGILE MCAL detector

3 short timescale events/features

E2: strongest at $T = -0.46s$, above 1.4 MeV



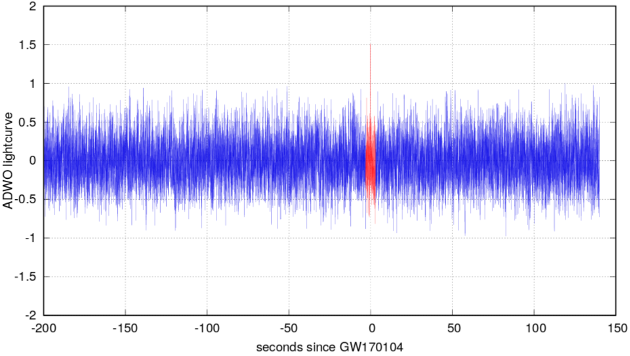
E2 event's post-trial probability is 3.4σ



If real, total energy is 10^{-7} smaller than the total black hole rest mass!

GW170104: ADWO (preliminary)

GBM data: $(-200, 140)$s interval around 04/01/2017 10:11:58.599 UTC.
ADWO: maximum is SPBPR=1.51, at $T \approx -50$ms, in the noise.



Integral SPI ACS: no signal.

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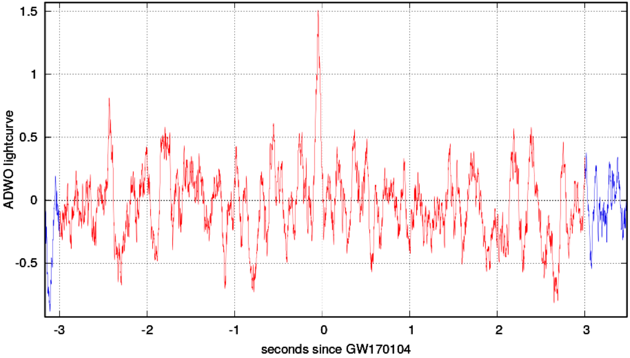


Integral SPI ACS: no signal.

GW170104 EM observations: AstroSat-CZTI and GROWTH (Bhalerao+17)

Good exposure ($\approx 50.3\%$) around T_0:

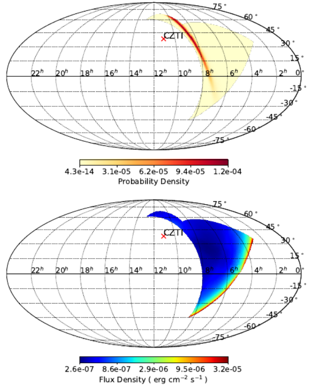


Figure 1. *Upper panel:* The LIGO sky position probability

No hard EM detection

CZTI upper limit: $\approx 4.5 \times 10^{-7}$erg cm$^{-2}s^{-1}$ for a 1 s timescale

GW170104 optical follow-up: ATLAS and Pan-STARRS (Bhalerao+17, Stadler+17)

ATLAS17aeu optical transient 23 hours later

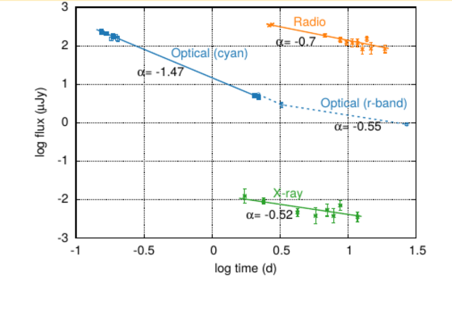


Figure 7. Flux evolution of ATLAS17aeu, the afterglow of GRB 170105A. Radio (AMI) data are shown in orange. In

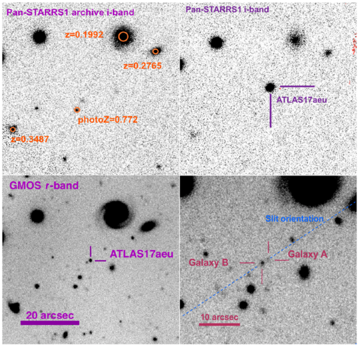


Figure 4. Top Left: The Pan-STARRS1 i_{P1}-band archive image (Chambers et al. 2016), showing no host down to $i_{P1} \simeq 23$ at the position of

ATLAS17aeu is an afterglow associated with GRB170105, with a chance coincidence of 2.6σ.

A long, soft GRB within a redshift range of $1 \leqslant z \leqslant 2.6$ would be consistent with all the observed multi-wavelength data.

Summary

GW EM counterparts

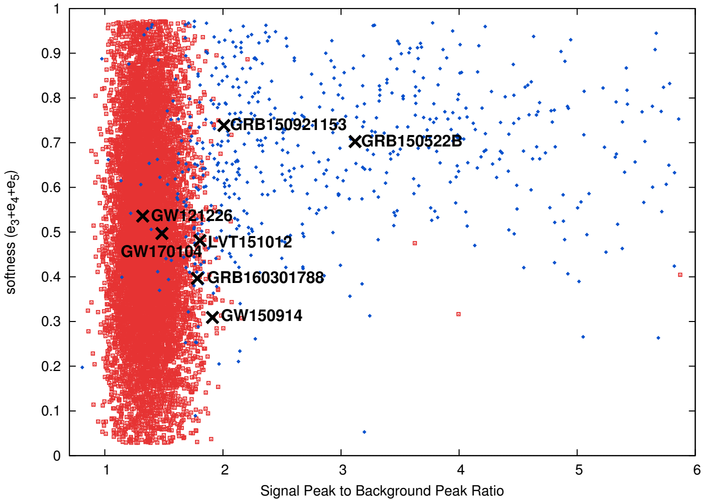
More GW events are needed!

ADWO

Efficient method looking for transients (GRB, non-triggered (s)GRBs, GW, *FRB, IceCUBE,* . . .)

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

ADWO efficiency



Red: 61.4 ks good CTTE data (14/09/2015) („background"?!)

Blue: Non-triggered (s)GRBs from Fermi's offline processing pipeline