Report on LIGO/Virgo Summer School

Gregorio Carullo

6 November 2016

1 Introduction

Gravitational waves (GW) are oscillation of the spacetime which travel at the speed of light, generated by the acceleration of a quadrupolar (or higher order multipole) distribution of mass, predicted by the equations of Einstein's theory of relativity a century ago.
Initially obtained as solutions in the weak-field regime, lately they have been theoretically proved to be solutions of the fully nonlinear Einstein's equations.
These waves can have two kind of orthogonal polarizations, relatively rotated by a 45° angle, known as + and x polarizations.
This theoretical prediction has been fully confirmed through the two detections accomplished by the gravitational wave interferometer aLIGO (Advanced LIGO) detector, part of the LIGO-VIRGO collaboration (LVC) on the 14th of September and 26th of December (Abbott et al.- "Observation of Gravitational Waves from a Binary Black Hole Merger"- Phys. Rev. Lett. 116).
The first observation was soon followed by a second one and it's worth noticing that a third candidate was announced by aLIGO, on the 12th of October, although only a detection statistics of 1.7 σ was achieved, which isn't enough for a detection statement (https://losc.ligo.org/events/LVT151012/).
Therefore we see that one of the main goals in GW data analysis is to develop new techniques to raise the detection's statistic, topic on which we'll return later.
The detection of this phenomenon took so long essentially because of the tiny effect (compared to classical physics scales) that these waves have on the structure of space-time, the strain (the difference in the arms lenght) registered in the detector being of the order of 10^{-24} m.
At these scales a big number of noise sources become important (Seismic, Shot, Radiation pressure, Mechanical vibrations, Thermal, transients and unknown glitches), which greatly affect the sensitivity of an interferometer.
To overcome the difficulties of detection raised by this overwhelming background, a number of different technicques and search pipelines have been developed, most of them suited for a specific kind of event or a class of events, while some just target excess of power in the detectors. In this report we'll refer to the two pipelines most suited for a coincident

GRB search, namely X-pipeline and PyGRB.
In the detections the sources of the detected events were in both cases massive black holes, so no electromagnetic counterpart was expected to be emitted by these objects, although investigations on possible coincident EM event has been carried on by the GBM team, finding a possible sGRB after 0.4 after the GW event, within the localization error box of GW150914 (Fermi GBM Observations of LIGO Gravitational Wave event GW150914, V. Connaughton et al.).
This connection is, for the present, unexpected and only future observation will clarify if this was just a chance (most probable possibility for now) or new environment features have to be taken into account.
But, of course, black holes aren't the only sources which are expected to give origin to GW radiation, on the opposite, the most expected sources of GW were binary neutron stars (NS) before the detection, essentially because of the higher expected merging rate of these objects, merging rate which could significantly change as soon as aLIGO will begin its second science run (O2) with an improved setting, and aVirgo will become fully operational in the next months.
Indeed they are expected to detect a larger set of events and so start to gather a statistical sample which could give much more precise estimates on merger rates of compact objects, besides BH mass distributions, Supernova detection, Stochastic background, equation of states of NS and much more.
It's been theoretically predicted by decades (REF4) that the coalescence of NS-BH or NS-NS and supernova events, will give origin to a wide range of EM signatures, in particular to γ ray photons, which can be detected by a number of experiments in orbit (FERMI, Swift, Konus-Wind, ...).
This feature of compact binary coalescences (CBC) in which at least one of the companions is a NS and supernova opens the door to multi-messenger coincident detection of the same event, which give rise to a much more broader field of possibilities than a single kind of radiation detection, as will be detailed below.
It's worth noticing that while the Long GRB-Supernova connection has been strongly proved by observational data, the Short GRB-Compact binary coalescence connection lacks of solid observations, fact that will immediatly change as soon as interferometers will start to collect GW data of these events.
These kind of considerations are well known among the LV community, a number of targeted searches and a system of detection alarms has been fully implemented by years, giving advantages to both side of the observational fields.
From one side having the GRBs times of arrival gives to a GW analysis a much shorter time window to work on, raising the detection sensitivity, from the other the missed detection of GWs permitted, for example, to exclude the hypothesis that the GRB051103 was originated in the nearby galaxy M81 (3.6 Mpc from Earth), whose localization overlapped with the one of the GRB, because no GW signal was observed within the GW detectors who were fully operational a that time.
Until now these kind of coincidence searches were always lead using "triggered data", which means using events registered in orbit, where they triggered the detector and were

recognized as real GRBs.
From 2012 November 26 a new kind of data from the FERMI GBM (Gamma-ray Burst Monitor) detector have become available, namely "untriggered data".
Untriggered data are events which didn't triggered the detector in orbit, but were recovered by the data collected by GBM only after being sent back to Earth and subsequently analyzed and recovered by a specifically-written code by Michael Briggs.
This code isn't fully completed and it's currenlty being optimized, but has already given a consistent set of data on which we can work on.
This new set of data gives us the chance to recover new GW signals which weren't found by other searches during O1, because, as we already mentioned (and we'll subsequently motivate more precisely), using a GRB as trigger for a GW search drastically raises the chance of a detection.
The purpose of my research project, completed under the supervision of Karelle Siellez, Laura Cadonati and in collaboration with the GBM team of Huntsville, was to help starting implement this new kind of search within LIGO selecting the sample of data, understanding the features of the GBM detctor and of the untriggered data, testing the actual quality of the untriggered candidates through a detailed spectroscopical analysis done using the specifically designed software RMFIT (developed by the NASA GBM group in Huntsville) and the running of X-pipeline and PyGRB in O1 data using these GRBs candidates as triggers.

2 Studying

The first couple of weeks and subsequent periods during my summer school have been dedicated to the study of GW (including the pipelines and detction technicques) and GRB.
Regarding the GW, on which I had a previous general background, I focused on understanding how they are produced by compact binaries, the theoretical techniques imployed to calculate the waveforms and the regimes in which Numerical Relativity is needed.
Then I briefly reviewed what are the main sources of noise and the corraleted use of the environmental channels used to exclude the noise (CIS, PEM), antenna factors and the advantages of a coincident GW-GRB search, namely:

- Sky location known from the burst, restricts parameter space;
- Raise the sensibility (larger horizon) due to the short time on which the search is performed (better background control);
- Two indipendent sources. GWs provide a largely complimentary set of information: component masses (whether black-holes are involved) and spins, system inclination, luminosity distance; while the EM counterpart provides information about EM energetics, a precise location, local and host environment, and red-shift.
- Measure of z from the burst, of D from the GW $\implies$ measure of Hubble constant and other cosmological parameters;

2.1 GW pipelines

The two pipelines used in this search are PyGRB and X-pipeline, so I focused on studying the techniques applied in these kind of analysis in order to recover and assign a statistic to each signal. Here I just outline their main features.

2.1.1 X-pipeline

X-Pipeline is a matlab-based software package for performing coherent (it gathers data from all availables detectors before starting the analysis) searches for gravitational-wave bursts in data from arbitrary networks of detectors. It's an nmodelled (doesn't use any theoretical model to match the data) and all sky (no restrictions on the sky angles of the signal) pipeline.
Given these features it's suitable for getting both the collapse of massive stars (thought to be the progenitors of long GRBs) for which we don't have any model regarding the GW signal emitted and the coalescence of compact objects (NS-NS or NS-BH, thought to be the progenitors of short GRBs).
The gravitational signal emitted by the progenitor of long GRBs is predicted to be a gravitational burst, the signal from CBCs has a wide variety of waveforms, depending on the position of the event within the parameter space of the progenitors, so it could be both a burst or a much more resolved signal.
X-pipeline is particularly adapted to find bursts being unmodelled, while a more detailed waveform could be much more easily be found with PyGRB, which is a modelled search, also if they can still be found within X-pipeline, although with lower sensitivity.
The online search of X-pipeline is guided by external triggers such as GCN notices, whose parameters are written in a perl script continuously checked.
The parameters needed to start the search are the GRB name, time, position and the detector to use (beside of the technical parameters of the pipeline itself of course).
The position is needed because, althought X-pipelines was born originally as an all-sky research, usually we take the triggers from satellites that give us the position of the event, so this parameter has become required. Of course this feature is possible being a coherent search.
X-pipeline was initially set to take into account Swift angular error boxes (of the order of arcminutes), then was optimazed to take into account the much wider FERMI angular error boxes (of the order of 10 degrees).
After the running of the pipeline, the results are written in a web page and email is send to the analyst.
The on-source time window is [t_0 -600 s; t_0 +60 s], adapted for the kind of duration of the signal.
This set up is a conservative one and take into account the most exotic models for the delay within a supernova. One could ask if using such an on-source window would affect the sentitivity of detection, but tests have been runned reducing the window to [t_0-5; t_0+1] which is the most probable window of delay between GWs and GRBs, but no sen-

sible increase in sensitivity was found. Of course reducing the on-source window would slightly reduce the computational cost, but the bulk of computational cost is the number of backgrounds.
The off source data is usually taken to be 1.5 h before and after the event, with 660 seconds off source segments, so the total time of running of this pipeline is usually hours.
X-pipeline is a two-stage analysis: trigger generation and post processing (apply background rejection tests, compute efficiencies, etc.).
After performing the generation of the triggers looking for excess of power in the detector, it performs pixel clustering in time-frequency plane, keeping the loudest event recovered.
Since the optimal analysis time is unknown, X-pipeline performs the analysis with different intervals of Fourier transform, to get both signals strongly peaked in frequency or time.
Each event is characterised by peak time, duration, bandwidth, significance (referring to Gaussian noise), various energy measures.
To estimate the sensitivity of the search and calculate upper limits (up to 90% cl), sine Gaussian waves and astrophysically real waveforms are injected.

2.2 PyGRB

PyGRB is a CBC pipeline based on a matched-filtering algorithm. The CBC waveforms are theoretically predicted, so we can project a bank of waveform on the data and calculate the matching between the signal and the expected waveform. The filtering is done requiring to maximize the signal to noise ratio (SNR). After the filtering the efficiency of recovery is calculated, through the injection of simulated signals, along with the False allarm probability (FAP), which is the probability that the loudest on source event was produced by the background. Of course the higher the number of significant events in the background, the higher the FAP.
To correctly calculate the SNR and translating it to a likelihood, a number of different tests are applied, χ^2 test, autocorrelation χ^2 test, coherence tests calculating the distribution within the parameter space of the events (a GW signal tends to match templates near to each other within the parameter space, glitches don't) along with the maximum distance of recovery .
All this tests contribute to producing the final statistic of the event or the exclusion distance in case of a non detection.
It's worth underlining that the time-slide technique gives a substantial reduction of the FAP, permitting to lower it below the level required for a detection claim.

2.3 GRB emission mechanism

Subsequently I read different books and lecture notes to understand:

- The GRB emission mechanism as predicted by the Fireball model, the accordance between simulations runned from this model and the observed events, along with the problems of this model;

- The history of GRB observations, the developments reached within each diffent observational era (from the Vela system, through BeppoSax and BATSE, finishing with Swift and FERMI);
- The features of environments and how they are inferred by observations;
- The time delay between GW and GRBs and other possible radiations (both neutrinos and other wavelenght EM observations);

In brief the process of emission, happening when two NS merge (or NS-BH merging) or a star explodes, consists in the central part collapsing into a BH, the outer layers are blown up and become accelerated relativist ejecta (spherical in first approximation, but due to the roational axis of the stars these jets are beamed along the rotational axis, this mechanism favors the leptonic emission, because heavier baryons are moved away from the centrifugal force, so that leptons are free to move and radiate in the center of the beam).
These relativist ejecta expand respecting conservation of energy, mass (because also if each layer's velocity is in itself relativistc, the relative velocity between two layers in non relativistic) and momentum, experiencing two different phases.
The first one is the acceleration phase, when internal energy is converted into kinetic energy, the Γ (Lorentz factor) is proportional to the radius and density decreases while the radius increases.
What happens in this phase is that ligher layers of matter scatter against, and then overcome, heavier and slower layers (no pressure waves), so a shock is created within the fireball, the shock stopping when the layers are ordered in increasing Γ.
When a faster layer overcomes a slower layer the electrons behind the faster layer are accelerated by the shock and emit GRB through synchroton or inverse Compton. At the end of this phase, the Γ of the outer layer saturated to a certain value when R_{sat} is reached. The acceleration phase has stopped and we find an highly relativistic outer layer with Γ_0 and M_0.
Now the ejecta meet the external media and when they hit each other two shocks are created (because some of the matter goes forward and some bounces back): the forward shock, which is the main responsible for the afterglow, and the reverse shock.
The forward shock is caused again by a faster external layer which hits the still matter of the media and accelerates it, the deceleration starting when the amount of mass of the external media swept-up by the ejecta is comparable to the equivalent mass of the ejecta itself.
The radius at which this deceleration starts is determined by the kind of media surrounding the source, in NS-NS or NS-BH GRB this is basically low density gas in empty space, which determine a large R_{dec}, but in collapsars stellar winds can give a much lower R_{dec}.
Since the afterglow is the mechanism caused by the deceleration of the electrons by radiating processes (why does the fireball stop? Because it hits the matter and radiates away energy creating the afterglow), by analyzing the afterglow and expecially the initial

phases, we can find the R_{dec} and deduce the kind of environment in which the event happened. It needs to be the initial afterglow because after a certain radius the saturation to a much lower value of Γ is common to every environment.
The electrons accelerate behind this forward shock and emit synchroton radiation, the flux spectrum of this radiation gives a power-law broken spectrum which agrees with the observations (this phase is the most constrained by the observation basically for this feature) till they get to some R_{nr} when the matter essentially slows down, becoming non relativistic, and stops.
The reverse shock starts from the same mechanism of the other two, when matter bounces back on the environment and can give both optical or X-rays/γ-rays emissions.
The model I exposed, called the Fireball model and widely accepted as the most reliable GRB model, permits to predict most of the observed features of the signals, especially the time variability of the peaks, given in this model by the velocity ($\sim$ c) at which the matter falls onto the central engine after forming a torus.
Regarding the delay between the GW and the GRB observations, no refraction delay is taken into account, because at these energies n $\sim$ 1.
The delay due to the emission mechanism is of $\sim$ ms and the delay between the merger and the jets is $\sim$ s.
So the total delay amounts to a few seconds within this model.
A final remarkable feature of GRB that is worth mentioning is that, although a full theoretical model which takes into account the full spectrum and explains consistently all the observational data hasn't been found yet, a function which fits most of the rate vs energy data is a smoothly broken power law combined with an exponential, of which we'll give the explicit definition later. Theoretical model have tried to reproduce this behaviour (which seems universal among GRBs) and some features have been completely reproduced, but a full achievement is yet to be reached.

2.4 General features and definitions about GRBs

To have a general understanding of the order of magnitudes of the events studied, I report a list of typical features of GRBs:

- HR= $\frac{\text{Counts in the higher band}}{\text{Counts in the lower band}}$;

  (Example: $HR_{BATSE}=\frac{\text{Counts in 320-700 KeV band}}{\text{Counts in 120-320 KeV band}}$)

- T_i= time at which i % of photon counts in a certain band are registered;

- $T_{90}=T_{95}-T_5$;

- Duration: 1 ms-1000s;

- Total energy radiated $\sim 10^{51}$ erg;

- Maximum flux peak: 1000 photons cm^{-2} s^{-1};

- Energy of photons: 100 KeV-100 GeV;
- Initially lots of counts with high energy, then lower counts with lower energy;
- Long GRB: $T_{90} > 2$s, $1 < \text{HR} < 10$;
- Short $T_{90} < 2\text{s}, 2 < \text{HR} < 20$, 10^{63} eV= 10^{51} erg of energy;
- Not certain if Short GRB are beamed, GW measurements could help understand.

3 Selecting the sample

In selecting the sample, we choosed the untriggered events which were coincident with the Observing run of aLIGO.
Although the official dates of running were 18-09-15 / 12-01-16, which gave us a sample of 8 events, subsequently we extended the time window of the sample to 12-09-15 / 19-01-16 because, although the run was "officially over", the Hanford and Livingston instruments were fully operational and calibrated data are present (remember that the first detection occured on the 14th of September during the engineering run, but since full sensitivity was already achieved, a detection was possible).
This time interval coincides with the one used by the O1 triggered GRB search and extended the sample from 8 candidates to 12 sGRB candidates.
Initially we made a first check within GraceDB (Gravitational Wave Candidate Event Database), which is a system to organize candidate events from gravitational wave searches and to provide an environment to record information about followups.
We checked for any coincidences with previously known triggered GRBs or GW candidates not confirmed, in a time window of hours within our events.
We found no coincidences with previously known events, except for the GCN notices of some candidate, reported below.
It's legitimate to ask, since a GRB search already exists within LIGO-Virgo, why do we need a new GRB search. The reason is pretty clear if we compare the triggered and untriggered GRBs sample used during O1 (not including IPN).
The triggered sample constists of 14 short, 65 long, 10 ambiguous or with no T_{90} (1), while the untriggered sample consists 12 short, 37 long (determination by Briggs's code still in progress, this number will grow).
So we clearly see that including untriggered data doubles the amount of GRBs data available, which is a reason good enough to explore the possibility to use these candidates as "GW triggers" and think to start a new specific search for these kind of events.

One important question one should ask, before using these candidates is if these data are within the LIGO/Virgo horizon.
The answer is, as far as we know, that they could be within the LIGO/Virgo horizon as well as as any other GRB, because no precise relation between distance and luminosity (or duration) is known, so there are no particular reasons to exclude these kind of candidates from a GW search.

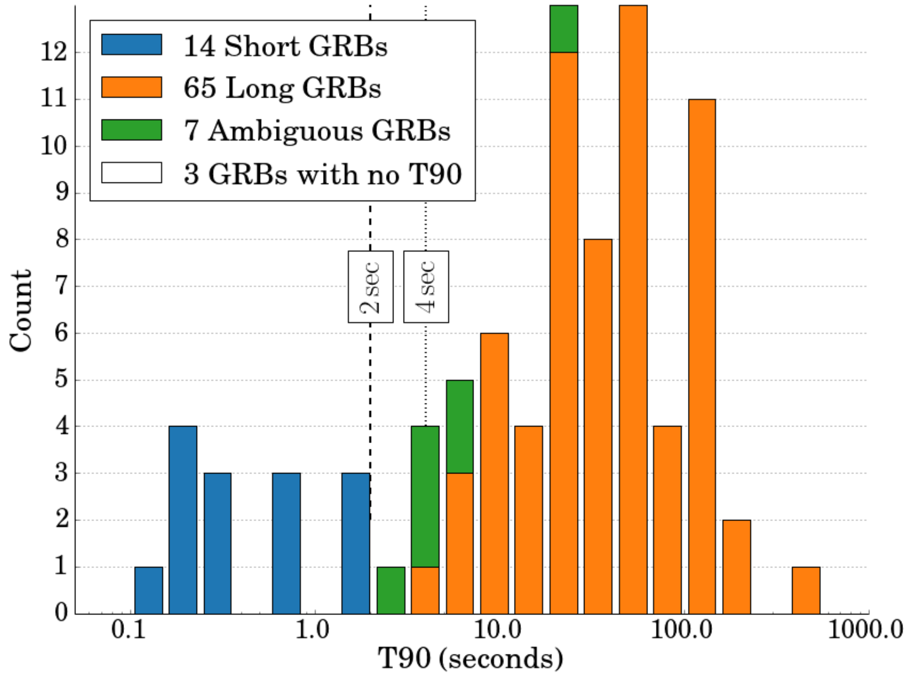

Figura 1: Plot of the distribution of events used during the O1 GRB search

In support to the last sentence, you can observe in figure 2 a sample of sGRBs for which we have z, showing no correlation between redshift and flux.

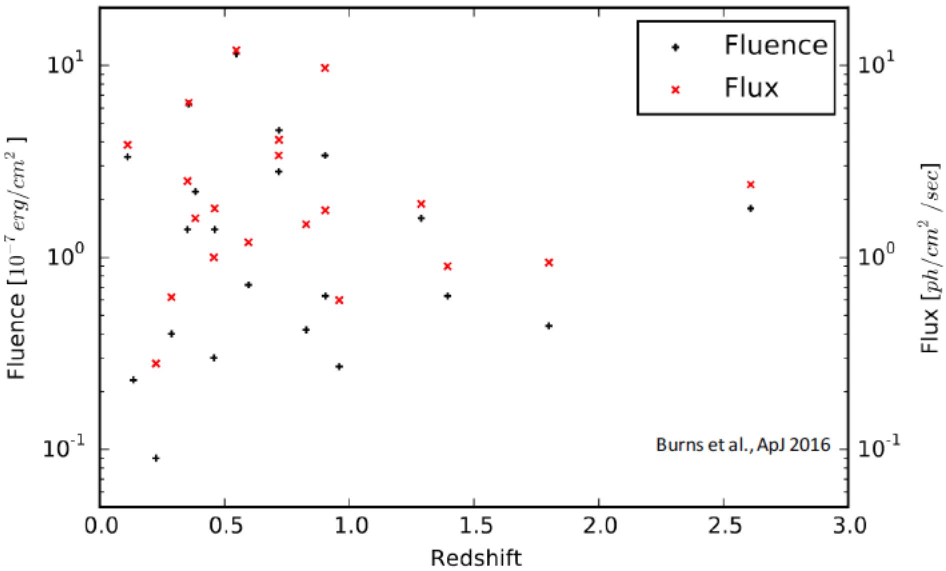

Figura 2: Plot of the distribution of events used during the O1 GRB search

Moreover in a recent article: "Evidence for a dual population of neutron star mergers from short Gamma-Ray Burst observations"- Siellez et al, 2016, ApJ submitted, a group from Nice which collaborates with Virgo/LIGO found evidence for a dual population of sGRBs, i.e. a population of nearer and fainter sGRBs. They proposed that these events would be produced dinamically within globular clusters from a NS-BH coalescence and investigated this possibility using Monte Carlo simulations. The advanced LIGO and Virgo observation of a high rate of NSBH mergers compatible with the dynamical formation in globular clusters wouldbe a confirmation of this hypothesis, since our events are exaclty faint sGRBs, it's worth exploring this possibility throughout this analysis.

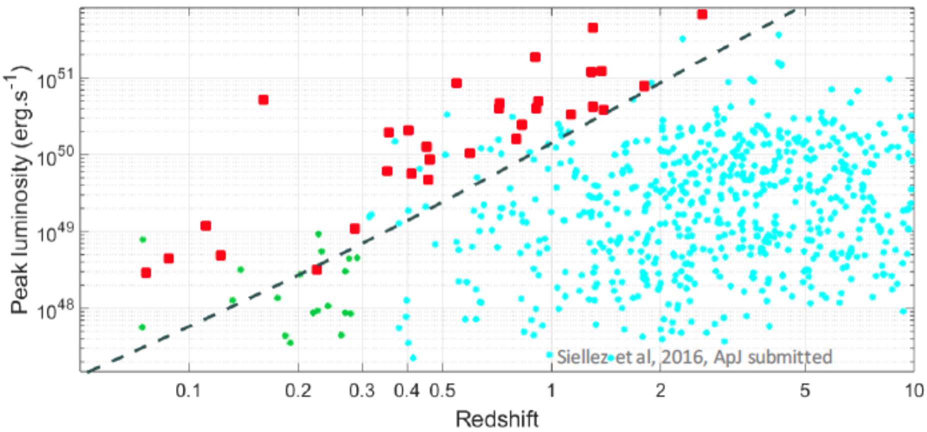

Figura 3: Plot of the distribution of events used during the O1 GRB search

4 Obtaining and cutting the data

The kind of data used in this analysis are single tagged time photons data (CTTE), the events were 2.5 σ above background in at least one detector, and 1.25 σ above background in at least two detectors (the geometry of the satellite was kept into account and events incompatibles with a distant point source were discarted), with a FAP $< 10^{-6}$ and found on timescales from 16 ms to 4 s. They were recovered in four energy channels (27 to 540 keV, 50 to 540 keV, 100 to 540 keV and 100 to 980 keV.) by the GBM detector, a large field of view (2/3 of the sky) telescope with low accuracy in burst localization and big angular error boxes ($\simeq$ 10 degrees), high and variable background, 2 μs of time resolution and 128 energy channels logarithmically spaced.
I downloaded the "Daily GBM data" of the days when the candidates were identified by Michael Briggs's code, from the GBM database.
I didn't used the Burst database, because it collects just the triggered events, we are analyzing untriggered ones, previously not recognized as GRBs from the onboard trigger. The goal of this analysis is to understand if some of these events can be classified as Short GRBs and what are the GRB's parameters in case of affermative answer.

Since the data cover all day, the tte files are very heavy, each day being $\sim$ 20 GB, which makes the goal of open it and analyze it directly with rmfit impossible, the computational time just to open the file is more than 10 hours.
So we had to cut the files before opening.
The procedure to do so was:

- Decide which detector to analyze, looking at the detectors which were "triggered" according to Michael's code.
  These events can be found here:
  http://gammaray.nsstc.nasa.gov/gbm/science/sgrb_search.html, clicking on the MET time of each event. Specifically we'll call "Principal detector" the NaI detector which registered the higher number of counts in the subsequent text;
- Choose the interval of the analysis in order to analyze the background which had to be subtracted from the event.
  We choosed to have an analysis interval of 400 s centered on the event time;
- Convert the UTC time of the event and the extremes of the interval to the number of seconds expired that day until the "trigger" time and use these numbers to calculate to which fraction of the day the event and the analysis interval belonged;
- Choose the tte file which contained all the fractions of the day in which the analysis interval is comprised (luckily no analysis interval was found to be contained in more than one single file, if that would happen we should have wrote a script to merge two files);
- Cut the files using the perl script of Peter Veres;

Another issue were the response files of the detector, which weren't contained in the Daily data, again because this files are untriggered, so we had to ask for them to the GBM team.

5 Spectroscopycal analysis

5.1 Analysis

We started the systematic analysis of the 12 Short GRBs candidates, with the exception of the 160116 event, because its data were corrupted and no cutting was possible.
Looking directly at these data is clear that the analysis is extremely difficult compared to the analysis of a regular GRB, because the signals we are investigating present only a small number of counts above the background, usually of the order of 100-200.
This implies that the signal is almost always buried within the noise, hardly distinguishable from actual noise if we look at just one detector's data. The difference of the situation between a triggered GRB and an untriggered candidate can be seen for example in figures 4 and 5 which show rate vs time. As you can see the main problem is the number of counts of the two kinds of events, of the order of 1000 in the first case and 100 in the second case.

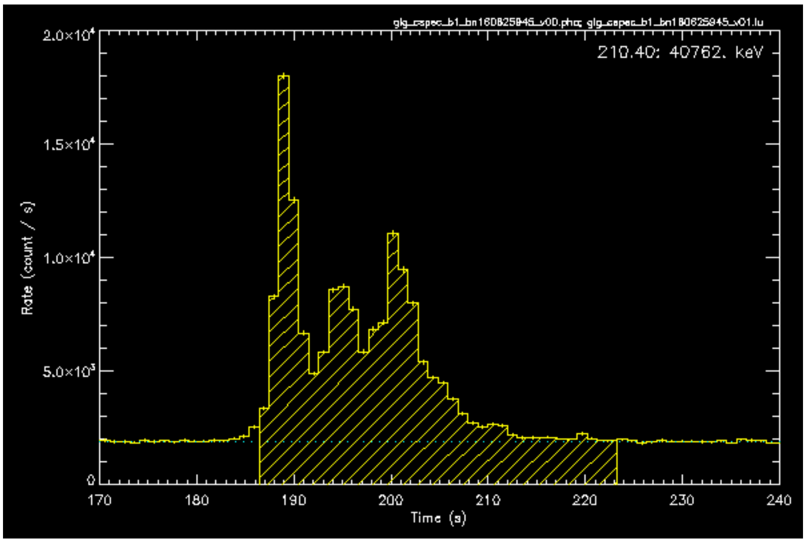

Figura 4: Typical signal of a triggered event in time domain.

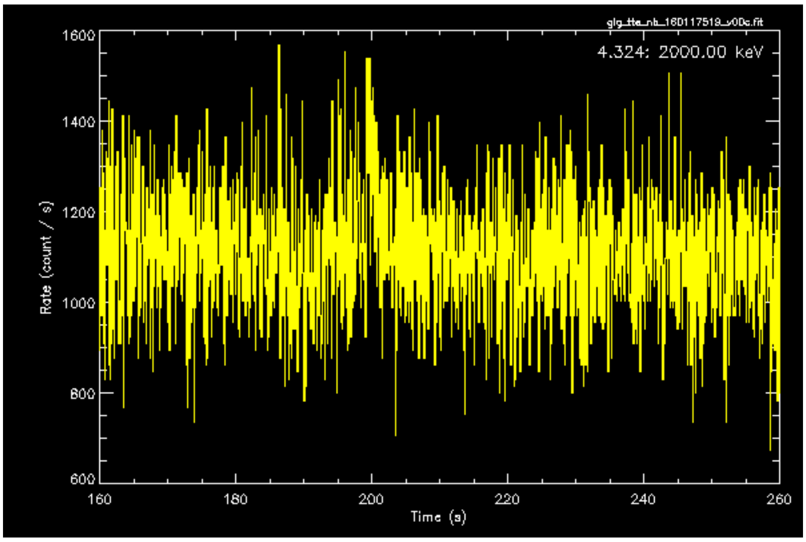

Figura 5: Typical signal of an untriggered event in time domain.

5.1.1 Source selection and rebinning

The small number of counts and the fact that the counts given by the noise were of the same order, if not bigger, than the actual signal has as a consequence that the selection of the source time is never straightforward and extremely hard in most cases.
Moreover there is no precise shape of the lightcurve (Counts in function of the time) of a GRB, because a vastly different population of GRB's lightcurve is known: they can have one or more spike, usually they have a fast rise-slow decay asymmetric shape, but

if the energy rises the peak is narrower and if the duration shortens the pulse is more symmetric (this problem should disappear for Long GRBs, thanks to both their duration and shape, which permits to distinguish them better from noise).

All of these features are qualitative ones and there's no theoretical strict restriction of the precise form of the lightcurve of a GRB, being too much dependent of the details of the event (the downfalling of matter on the central engine) which generated the GRB.

Being our events short, we shouldn't expect always the fast rise-slow decay shape as explained above.

An example of this difficulty can be seen in figures 6 and 7 in which is not clear what is the source's time and what is just noise. Both of the two source selections are a priori possible (in this figures isn't showed, but another possibility is that the source selection starts before the one we choosed, option which we had verified).

This fact complicated the analysis (because short duration and low number of counts (compared to regular GRBs) implies that duration and bin's height is completely similar to noise) and required that each analysis had to be done multiple times, each time with different source's selection, to discriminate what is truly a possible signal and what is just noise looking at the results of the fitting procedure in the principal detector (we call principal detector the NaI detector in which the signal was better seen).

The solution of taking as signal only the coincident signal between two or more detectors is not accountable because the signal is directional and most of the times it was clearly seen just by one detector and barely seen in other for geometrical reasons.

The problem of time selection could be solved, for example, by having a far better knowledge of the background, which for this kind of experiment is pretty complicated, seen thee high number of astrophysial sources. A way to improve the background understanding could be through poissonian simulations to reproduce the background and partially this has already been done, because Briggs's code determins the FAP of the candidates being generated by the background exactly through Poissonian likelihood, but a precise method to determine the T_90 of these candidates hasn't been found yet.

This problem is enhanced when we require that the signal has a SNR of at least 20, implementing the rebinning.

When we do so, a typical result is as in figure 8. Of course we tried different rebinnings, because possibly in a signal so weak we cannot require a SNR as high as for a regular GRB, being the signal usually weaker than the standard ones, but no improvements were found in the fitting procedure, because fitting is always done at the best resolution in energy domain.

The energy interval selection has been performed in the standard way, restricting the analysis to the interval [8;900] KeV, [200;40000] KeV respectively for the NaI and the BGO detectors. Regarding the rebinning in energy (which doesn't change the result of the fit, since the fit is always done at the highest resolution), we searched for the best procedure which gave a good visualization of the data, the standard procedure was to combine the bins first by 4 and then optionally to combine them again by 2, the last part being usually applied on the higher frequency part of the spectrum, where the channel division is more thick (the energy channels have a logarithmic division).

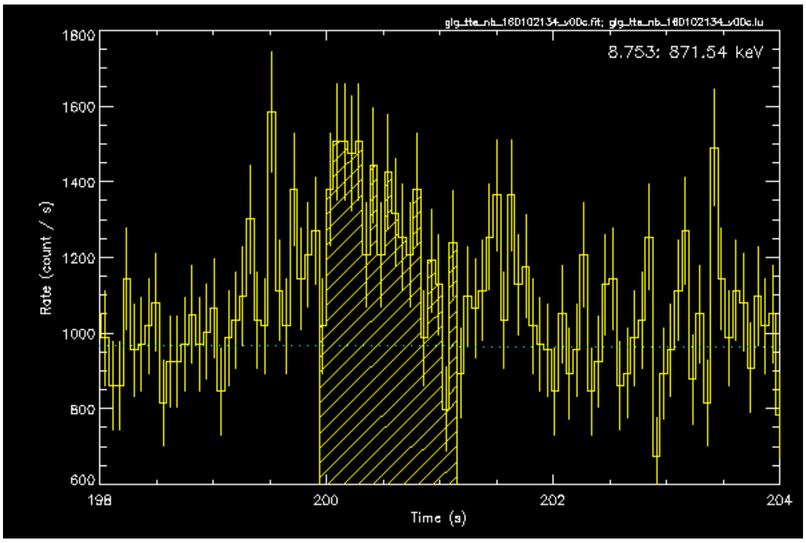

Figura 6: Source selection of an untriggered candidate

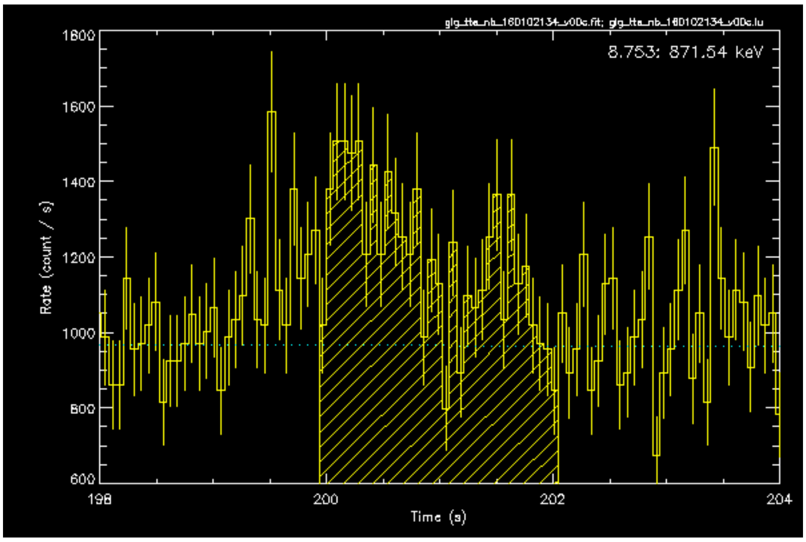

Figura 7: Source selection of an untriggered candidate

5.1.2 Background selection

Usually the background is selected enough far from the source to have no superposition with the event time and during an interval where no other significant event is present (so we don't overestimate the background if there is a noise event which gives an high number of counts for example).
However in this case all the surrounding background was "significant" compared to the event, so choosing the background in an interval with the lower number of counts wasn't

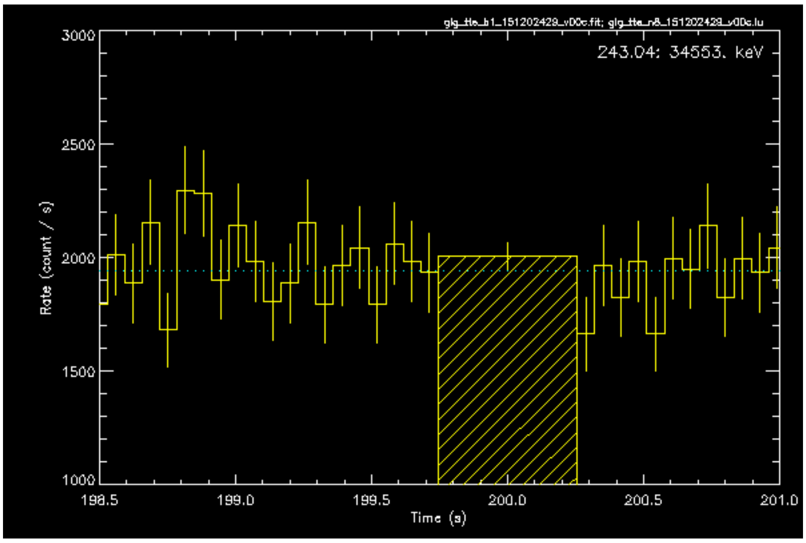

Figura 8: Typical rebinned signal

the right choise, because the fact that the noise is so important around the signal is something which we have to take into account in our analysis.
So the better option seemed to us to choose a standard background interval composed by two intervals of 20 s each centered 30 s before and after the signal, as you can see in figure 9. This choise of the background insures that no match with the actual source is present.
We tried to fit the background with different numbers of parameters, usually 1 parameter was enough, but there were cases when a fit with 3 parameters was performed in order to better fit the background.
A common feature of these signals was that the background sometimes accounted for all the counts registered in the detector over almost all the energy domain (or even overestimated the signal in certain cases), as can be seen in figure 10 (to be compared with the spectrum of a typical triggered GRB 11) which shows the rate vs energy of a signal. The blue curve is the background and the yellow curve is the signal registered, so the real event is the difference between the curves, which is the quantity that is going to be fitted.

5.1.3 Fit

The only degree of freedom left to the fit procedure was the choise of the fitting model at this point, nevertherless the fitting has revealed more complicated than one could expect, basically because for these kind of data were the counts are low, we cannot rely on the χ^2 test, which has good properties of model estimation only with a statistical sample. Of course we can still use the sum of residuals as a parameter that measures the difference between our model and the data, but we cannot translate this number into statistical precise statements, since the sum of residuals is distributed as a χ^2 only with

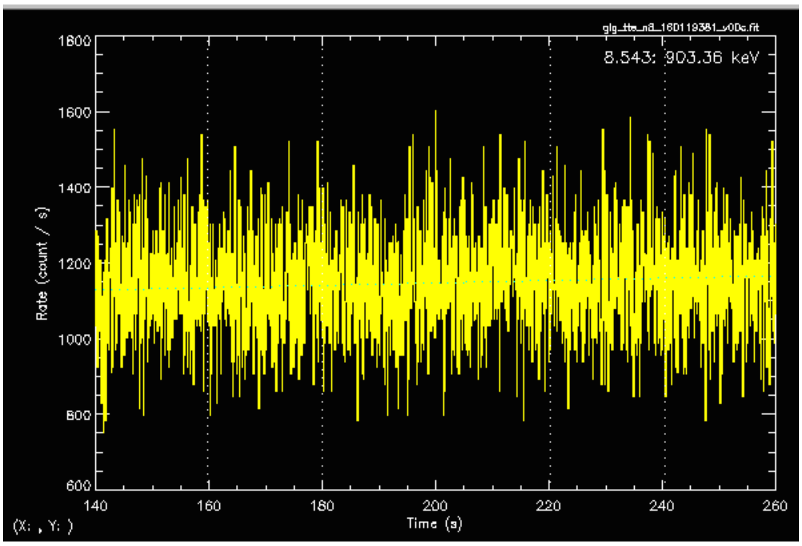

Figura 9: Background selection in time domain

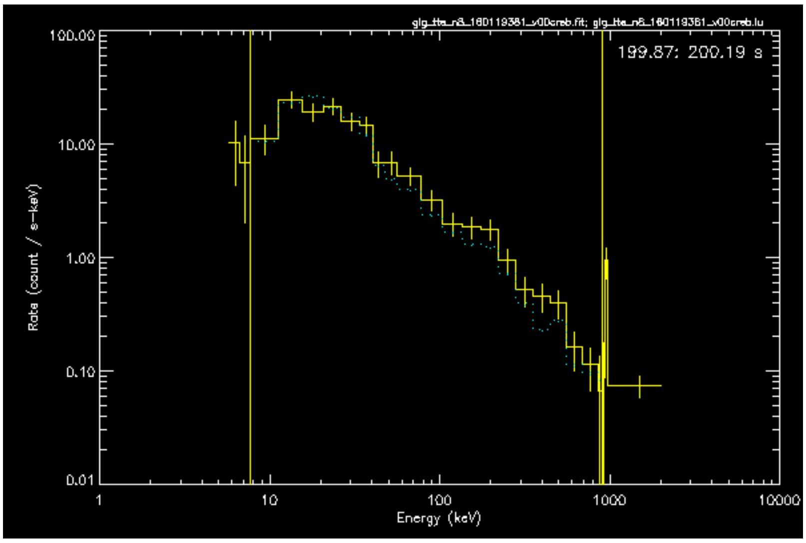

Figura 10: Typical rebinned spectrum of untriggerd GRBs

a sufficiently high number of measures.
We used therefore the C-stat, which is on Poisson likelihood, suited to deal with low-number of counts. However these statistic is suited only to compare different models and cannot be used directly to estimate the "goodness" of a fit, although the fit requirement is to minimize C-stat, there is no analytically expected a priori value for the fit, nor probability distribution for deviations from that value.
So we could only use the fit to discriminate the different models. When we wanted to discriminate between different source selections we compared the convergence of the fit

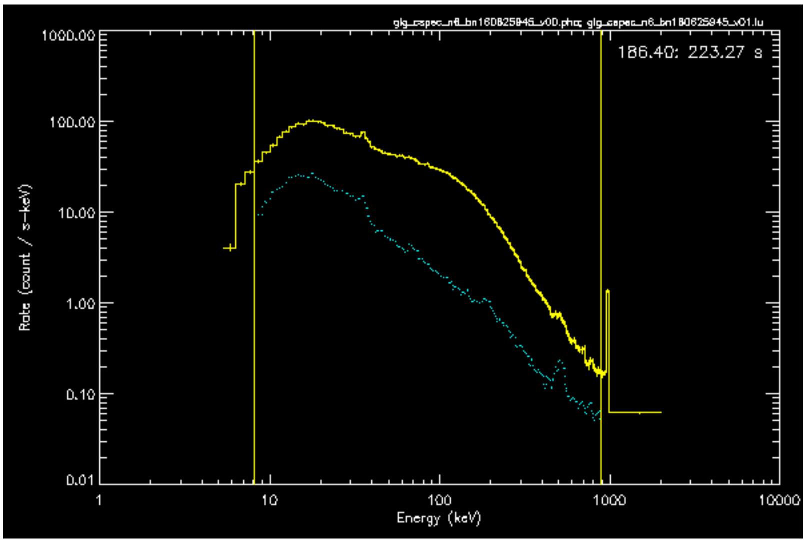

Figura 11: Typical rebinned spectrum of triggerd GRBs

by looking at the match between the fitting curve and the data (sum of residues) and at the relative errors given by the fitting procedure (if a model gave huge relative errors which didn't determined the spectroscopycal properties of the signal we discarted it).
In each analysis we tried different models, but usually the ones which showed good convergence were these three (recall that these are all phenomenological model, there is no preferred theoretical model):

1. **Power Law:**

   - A = amplitude in photons s^{-1} cm^{-2} keV^{-1}
   - E_{piv} = pivot energy in keV,
   - λ = index.

$$f_{pl} = A(\frac{E}{E_{piv}})^{\lambda}$$

2. **Band's model:** (ApJ, 413, 281, 1993), Epeak parameterization, a different parameterization than that given in the ApJ article.
   The relation is $E_{peak} = E_0(2 + \alpha)$.

   - A = amplitude in photons s^{-1} cm^{-2} keV^{-1}
   - E_{peak} in keV,
   - Low-energy index α
   - High-energy index β;

$$f_{Band} = A \left(\frac{E}{100}\right)^{\alpha} \exp\left(-\frac{E(2+\alpha)}{E_{peak}}\right) \qquad \text{if } E < \frac{(\alpha-\beta)E_{peak}}{2+\alpha}$$

and

$$f_{Band} = A \left(\frac{(\alpha-\beta)E_{peak}}{[100(2+\alpha)]}\right)^{\alpha-\beta} exp(\beta-\alpha)\left(\frac{E}{100}\right)^{\beta} \qquad \text{if } E \geq \frac{(\alpha-\beta)E_{peak}}{2+\alpha}$$

3. **Comptonized:** The relation between the old and new parameterizations is $E_{peak} = E_0\ (2 + \alpha)$.
   - A = amplitude in photons s^{-1} cm^{-2} keV^{-1}
   - E_{peak} in keV,
   - E_{piv} = pivot energy in keV,
   - λ = index.

$$f_{comp} = A\left(\frac{E}{E_{piv}}\right)^{\lambda} \exp\left[\frac{-E(2+\lambda)}{E_{peak}}\right]$$

We runned the fit with each of these models in the principal detector, selecting the one which gave the better results in fitting the spectrum of our signal. Then we used the best models to fit all the others detectors singularly, to determine if the fitting procedure gave problem with one particular detector and to compare the convergence of the fit in the different detctors which had received different number of photons from the signal. You can see an example of fit of an untriggered candidate (both in one and multiple detectors) and the comparison with a triggered one in figures 12, 13, 14 and 15. Usually, for the candidates confirmed, the fit showed good convergence within one or two NaI detectors, although the BGO detectors gave bad fitting results, probably connected with the already mentioned feature that the counts registered in the high frequency part of the spectrum were almost always given entirely by the background, so the high frequency part of the spectrum covered by the BGO detector isn't well fitted.
Then we always fitted all the detectors together, again with each of the four model to check if one of the models who gave bad results in the principal detctor had better convergence when employed on all the detectors. When performing fits on multiple detectors we of used each model together with the "Effective area correction model", which took in account the effective area utilized by each detector.
Examples of fit in single and multiple detctors and the comparison with a fit done on a triggered candidates are shown in figures 6 The model who gave better fit results was usually the "Power Law model". This feature has to be ascribed mainly to the fact that this is the model with the lowest number of , so the easiest to constraint (just two: amplitude and power index).
However, when the fit with the Band model gave mild convergence we always reported also the the fit with this model, being the most common used and the one which has successfully shown to best fit most of the GRB's signals.
One detail must be pointed out: at a first glance the amplitude of the fitting function

appears sistematically smaller than the amplitude of the displayed data. This effect is due to the fact that since for these candidates we have very few experimental points, when the detectors registers 0 countr Rmfit automatically plots the 2σ upper limits, so most of the points displayed are upper limits.
Rmfit doesn't fit the upper limits, but of course it fits the points which are recognized as zero, because they are just as any other experimental data and the amplitude is choosed accordingly, so it's not sistematically smaller than the data, just sistematically smaller than the upper limits, as it should be, but of course it's largely reduced by the points compatible with 0.
This is the reason for the main problem of the fitting parameters given as results of this analysis: the fact that the amplitude is often compatible with 0 within the experimental error.

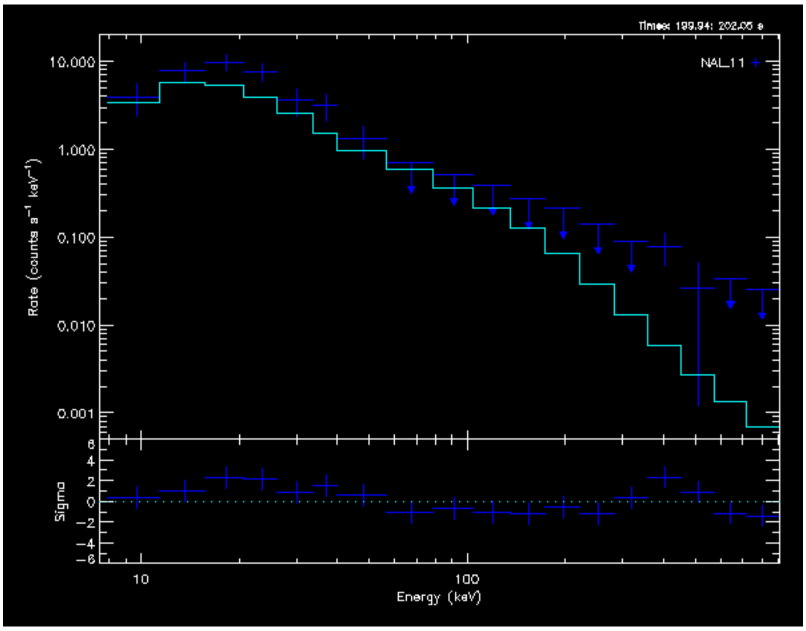

Figura 12: Fit of an untriggered signal in one NaI detector

5.2 GCN confirmations

Four candidates were confirmed by other observations:

- Candidate 151205 23:54:13 (classified as GRB 151205C): GCN circular
- Candidate 160102 (classified as GRB 160102A): GCN circular
- Candidate 160117 (classified as GRB 160117B): GCN circular
- Candidate 160119 : Michael Briggs reported on Untriggered short GRBs candidates an ACS confirmation, but we found no confirm on the GCN database.

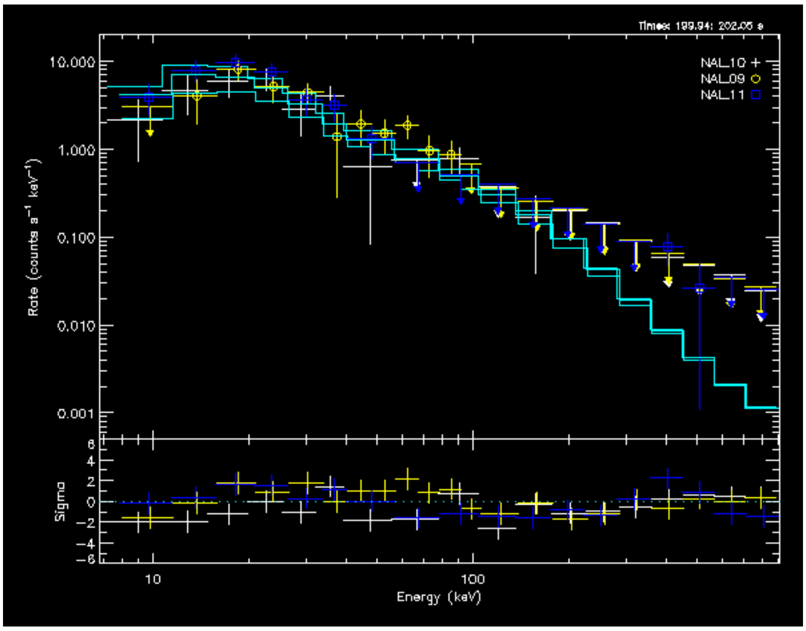

Figura 13: Joint fit of an untriggered signal in all detectors

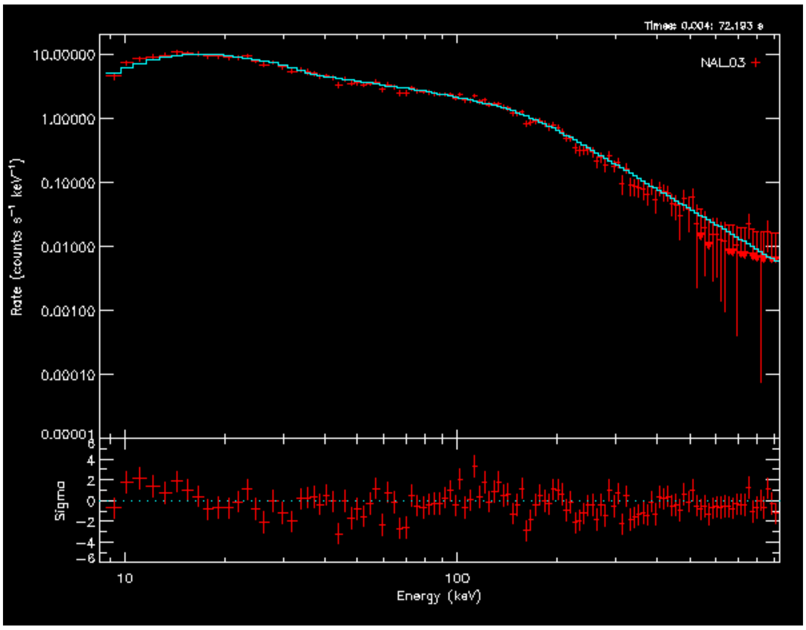

Figura 14: Fit of a triggered signal in one NaI detector

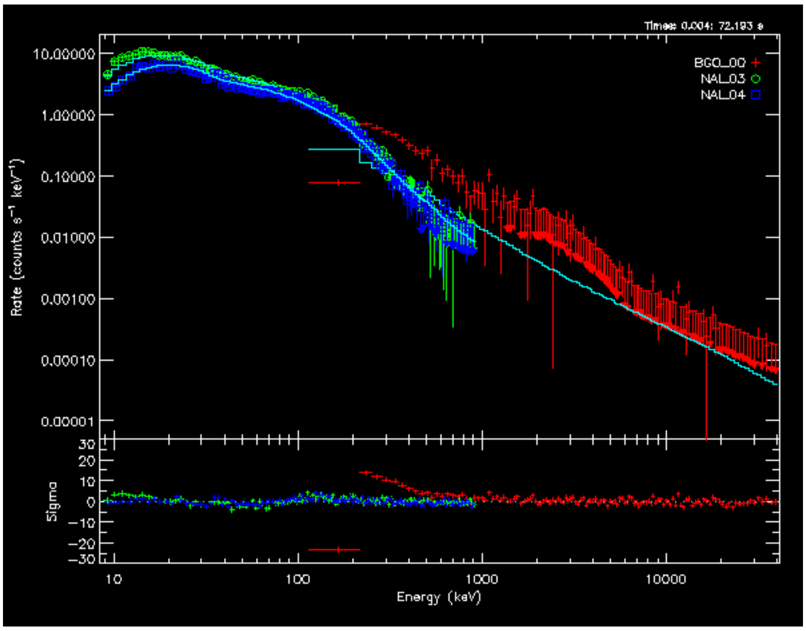

Figura 15: Joint fit of a triggered signal in all detectors

5.3 Possible candidates

As mentioned above the features of this kind of signals made this analysis much more difficult than a standard GRB analysis, being the noise inside the detector often overwelming compared to the signal.
We discarted the signals for which no fit in at least two detectors converged.
The only signals analyzed that can possibly be a sGRB, using this criterion, are the candidates (we report the final considerations of each single analysis):

- **151205A:** Relying on the analysis performed, the parameter determination of the 05/12/2015 A candidate cannot be performed entirely (we have no informations about the amplitude specifically).
  However the fitting procedure gave coherent results regarding α (within 2 σ) in all the detectors except the n_1 and consequently this is one of the most promising candidates to be a new sGRB.

- **151205B:** Relying on the analysis performed, the 15/12/2016 B candidate can be classified as a new sGRB, because although the high frequency component is not well determinated (the fit in the BGO detector didn't converged), its parameter estimation according to the Power Law model is solid and coherent between the fit in the principal detector and the fit in all the detectors.

- **160101:** Relying on the analysis performed, the 01/01/2016 event is a probable candidate to be a new sGRB, although for a full detection statement a deeper analysis is required, because the fit showed poor convergence and the parameter determination is far from precise, due to the high noisiness of the data.

- **160102:** The signal has an anomalous behaviour at high frequency, wheter it doesn't have any high frequency component or this component is covered by noise. Due to the low number of counts the amplitude is also poorly determinated, being compatible with 0 within the error.
  Despite these features, this signal is the most promising candidate to be a new short GRB, showing clearly in all the detectors a low-frequency behaviour typical of a short GRB well fitted by a Power-Law model.
  As you can read in the circular the results on parameters reported by the Konus-Wind team are compatible, within the 1 σ error, with the one obtained in our analysis, confirming the determination of this candidate as a new sGRB (our determination of the power law index was (-2.04 $\pm$ 0.08)):
  Fitting the K-W 3-channel time-integrated spectrum (from $\simeq T_0$(MAXI)-3.6 s to $\simeq T_0$(MAXI)+2.28 s) by a simple power-law model yields a power law index of -2.05(-0.15,+0.23), $\chi^2 = \frac{0.5}{1}$ dof."

- **160117:** Relying on the analysis performed, the 17/01/2016 can definitively classified as a new GRB, because the fact that the determination of the parameters isn't coherent between all the detectors is connected with the low number of counts in the high frequency range, which spoils the fitting convergence in the joint fit, but the fitting procedure in the NaI detectors is completely reliable and the fit showed good convergence with the Power Law model.
  Moreover, as cited above, this signal was reported in a GCN circular confirming the parameter determination obtained in our analysis (our value of the power law index was (-2.34 $\pm$ 0.05)):
  "A spectrum formed from the WT mode data can be fitted with an absorbed power-law with a photon spectral index of 2.36 (+0.08, -0.07)" and reporting the redshift mesurement: z = 0.86 $\pm$ 0.01.

- **160119:** Relying on the analysis performed, the 19/01/2016 event is a probable candidate to be a new sGRB, although for a full detection statement a deeper analysis is required, because the fit showed poor convergence and the parameter determination is far from precise, due to the high noisiness of the data.

- **160120:** Relying on the analysis performed, the 20/01/2016 candidate is a one of the most promising candidates to be a new sGRB.
  The amplitude determination of the signal is weak and only a small number of counts were seen in the detectors, but the parameter estimation gave coherent results across all the detectors and the fit showed good convergence within all the detectors.

5.4 Results

To conclude this section we present a brief summary of the results obtained:

- Mean relative errors on Power Law index: 20 %
- Amplitude sometimes compatible with 0, within the errors.
- Amplitude systematically lowered by the 0 counts in most of the energy channels (displayed as upper limits);
- Photon flux $\simeq$ 1 ph cm^{-2} s^{-1} (same as typical GRB), mean relative error: 15%;
- Energy flux $\simeq 10^{-7}$ erg cm^{-2} s^{-1} (same as typical GRB), mean relative error: 25%;
- Confirmations of all of the 4 GRBs (GRB 151205C, GRB 160102A, GRB 160117B, GRB 160119) seen by other satellites (MAXI, Swift, ACS), plus confirmation of 3 new candidates;
- 7/11 candidates confirmed;
- Complete agreement (within 1 σ) with all the parameters determined by other satellites;
- Just one redshift available (16/01/17): z=0.86 ± 0.01;

Candidate	Amplitude ($ph \cdot s^{-1} \cdot cm^{-2} keV$)	Index	Ph flux ($ph \cdot s^{-1} \cdot cm^{-2}$)	En flux ($erg \cdot s^{-1} \cdot cm^{-2}$)
15/12/05A	0.0023 ± 0.0005	-1.62 ± 0.14	1.9 ± 0.5	(3.9 ± 0.9) 10^{-7}
15/12/05B	0.0030 ± 0.0008	-1.13 ± 0.19	1.4 ± 0.4	(2.51 ± 0.81) 10^{-7}
16/01/01	0.0024 ± 0.0024	-2.36 ± 0.61	4.16 ± 1.6	(2.0 ± 1.4) 10^{-7}
16/01/02	0.0034 ± 0.0003	-2.04 ± 0.08	2.32 ± 0.44	(1.65 ± 0.33) 10^{-7}
16/01/17	0.0014 ± 0.0002	-2.62 ± 0.04	3.65 ± 0.39	(1.43 ± 0.15) 10^{-7}
16/01/19	0.0042 ± 0.0015	-1.4 ± 0.3	2.2 ± 0.9	(4.1 ± 2.1) 10^{-7}
16/01/20	0.0061 ± 0.0012	-1.61 ± 0.2	5.62 ± 3.5	(7.6 ± 3.1) 10^{-7}

Table 1.1: Results of the fits

6 GW analysis

The analysis of the gravitational wave data with X-pipeline, after a few problems due to the fact that the code was recently upgraded and slighlty changed, is still being carried out at the present moment, so I cannot present any result on this part of my work.
As soon as this analysis will be complete, another search, specific for sGRBs will be carried out with PyGRB, searching for compact coalescences.
Another aspect of the search which is currently being carried out now within the GeorgiaTech group is the Detector characterization of the data near these events, to study quality, glitches and possible vetoes to apply to these data.
All these efforts should culminate in a single article that will probably be presented next year, comprehensive of all the aspects of the research.

7 Future developments and problems to solve

To conclude this report, we cite some of the future developments we wish to obtain in the near future, together with problems of interest remained unsolved:

1. As soon as LIGO and the GBM team will have an official collaboration and they will share the codes, get a precise understanding of how translating Briggs's code FAP of an untriggered GRB event into an improvement of the GW FAP in the case of a joint detection;

2. Gain a better understanding of the signal time determination (requires understanding of the noise's features);

3. Create a catalogue and construct the distribution of the redshifts from these GRBs (requires statistical sample).

4. Can we change merger rates? Can we improve the present estimates?

5. Compare of the z from the untriggered GRBs and the triggered ones.
   Are they ystematically nearer of farer than the triggered ones?
   Are they within LIGO horizon?

6. Find a method to calculate the T_{90} for these candidates.

8 Reports

In each part of my research project I produced a report of my work and a summary of what I studied. Moreover I wrote a full report of each single spectroscopycal analysis which contains all the details of what I've done. If needed these documents are of course available on request.