Prospects about X- and gamma-ray counterparts of gravitational wave signals with INTEGRAL.

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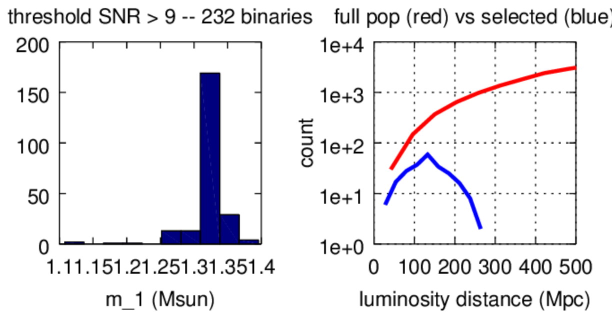
Abstract. By extrapolating the number of detections made during the first LIGO science run, tenths of gravitational wave signals from binary black hole mergers are anticipated in upcoming LIGO Virgo science runs. Finding an electromagnetic counterpart to compact binary merger events would be a landmark discovery. The search for such counterpart is challenging for a number of reasons, such as the poor resolution of source position reconstruction from the gravitational wave observations alone, and the weakness of the expected electromagnetic signal. In this poster, we evaluate the ability of current wide-field X- and gamma-ray telescopes aboard INTEGRAL to find such counterparts. We present the result of an end-to-end simulation for estimating the fraction of the sources that can be followed up, and the fraction of counterparts that can be detected based on different models.

Motivations

On Sep 14 2015, the two LIGO interferometers made the first direct detection of gravitational waves (GW). A next step would be to detect an electromagnetic (EM) counterpart associated to a GW event. This would inaugurate a new, multimessenger era in the astronomy history. We address the question of the joint detectability of GW events by Advanced LIGO, and associated EM events at high-energies by the INTEGRAL mission. We produce an end-to-end simulation of the search for gravitational-waves from binary neutron star mergers and follow-up observation seeking a possible electromagnetic counterpart at high-energies. This study is similar to the one done in (Patricelli et al. 2016) with Fermi.

Monte-Carlo simulation of gravitational-wave events from neutron-star binary mergers

We start with a simulated catalogue of 6 millions Milky Way-like galaxies distributed to $z \sim 0.12$. To those galaxies, we associate binary neutron star (BNS) mergers with mass distribution and rate of R=23.5Myr^{-}3 per galaxy according to Model A (solar metallicity) of (Dominik et al. 2012). This results in a population of 14 000 mergers for a 100 year simulation.



We simulate GW signals corresponding to the binary mergers (using model "TaylorT4") and inject them into Gaussian noise coloured according to the "optimistic" power-spectral density anticipated for the 2nd LIGO/Virgo run O2 (Abbott et al. 2016). We select signals with $\mathrm{SNR}_{\mathrm{combined}} > 9$ corresponding to a false-alarm rate FAR $<$ 1/month. The average range BNS is 126 Mpc for this selection.

This results in 232 selected merger signals over 100 years which corresponds to $\sim$ 1 merger over the 6-month duration of O2. We distribute those events randomly in time over the expected period of O2 from Nov 2016 to May 2017. We recover GW signals using matched-filtering techniques and reconstruct the posterior skymaps giving the position of the source using the BAYESTAR pipeline (Singer & Price 2016). With two detectors only, the position uncertainty is large and contained in a window of 700–2000 square degrees.

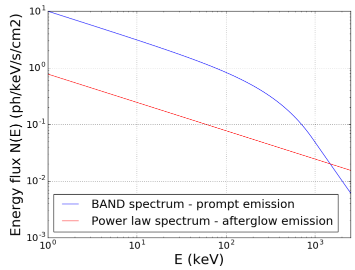
Electromagnetic emission model from neutron-star binary mergers

Compact binary mergers involving at least one neutron star are considered to be plausible progenitors of short gamma-ray bursts (GRB). Short GRBs is a subset of the whole GRB population with duration shorter than ~2 seconds. Short GRBs have also a harder spectrum. Prompt emission is attributed to dissipation within the collimated ultra-relativistic jet and is therefore strongly beamed. It is followed by slowly decaying afterglow, observed from radio to GeV, produced by the interaction between the ejecta and the ambient medium surrounding the GRB progenitor. Afterglow emission is originally also strongly beamed, but as the outflow decelerates, the emission becomes progressively more isotropic.

In our simulation we assume that every BNS merger is associated with a short gamma-ray burst. We simulate synthetic prompt GRB and a hard X-ray afterglow, assuming the following simplified model.

Prompt emission

We model the prompt emission spectrum by the cut-off power-law model. This model is a variant of the Band model (Band et al. 1993) where high-energies have been suppressed because they are generally not well constrained by the observations. For simplicity we assume the same prompt emission spectrum for all synthetic GRB, with $\alpha_{\mathrm{BAND}} = -0.5$ and $E_{\mathrm{peak}} = 600$ keV, close to the average short GRB spectrum observed by Fermi/GBM (Gruber et al. 2014). We also assume fixed duration of the prompt emission of 1 s and fixed isotropic equivalent luminosity of 10^{50} erg cm^{-2} s^{-1}.



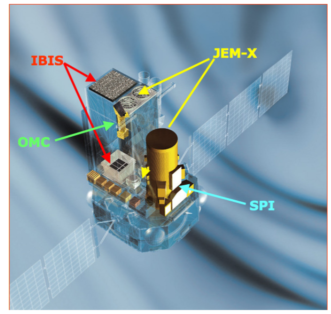


Figure 1. (*Left*) Prompt and afterglow emission spectra of short GRBs. Fluxes have been normalized with respect to the INTEGRAL energy band [75 , 2000] keV. (*Right*) Instruments embarked on INTEGRAL satellite.

The principal source of uncertainty on rate of GRB detections associated with the BNS mergers is the beaming factor of the prompt emission. We assume a fixed beaming angle of 10 degrees. This angle is roughly compatible with the observations of the total short GRB rate inferred from our BNS population.

Hard X-ray afterglows

We assume that every BNS merger produces a hard X-ray afterglow. Although afterglows in the hard X-rays are rarely observed, it is not unreasonable to assume that they are as frequent as gamma-rays, but observed much less frequently due to observational limitations.

There are indications that such afterglows are present in the most luminous GRBs occurring about once in few months (2% of the sky observed by INTEGRAL). When hard X-ray afterglows are observed, INTEGRAL observations reveals very high SNR. For instance, GRB120711A was seen in INTEGRAL/ISGRI and JEM-X for about 8 hours (Martin-Carrillo et al. 2014). The bright hard X-ray emission afterglow found to be related to the bright gamma-ray afterglow, observed by Fermi/LAT in the energy range above 100 MeV. In particular, it had the same spectrum, power-law with a slope of -2.

We assume a spectrum similar to GRB120711A, but rescaled to the total EM luminosity of a typical short GRB - 10^{50} erg^{-2} s^{-1}. We extrapolate this spectrum to the off-axis case using Model I in (Patricelli et al. 2016).

The INTEGRAL mission and possible follow-up strategies

The INTEGRAL satellite carries a combination of pointing instruments, covering wide energy range from 3 keV to 10 MeV (ISGRI, PICsIT, JEM-X, and SPI) with field of view up to 900 deg^2. Active follow-up: We assume that every GW alerts reported by LIGO/Virgo is followed by INTEGRAL pointings. Typical latency of INTEGRAL observation is about 1 day but may be lower in some circumstances. We compute the flux at several moments of time, and compare it with ISGRI sensitivity in 100 ks observation. Passive follow-up: In addition, INTEGRAL/SPI-ACS and IBIS are capable of detecting bright transients from every sky direction.

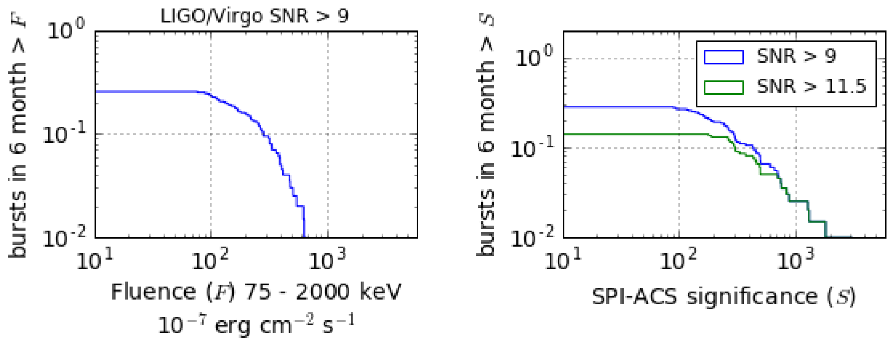


Figure 2. (*Left*) Cumulative distribution of the detected fluences by INTEGRAL in the LIGO/Virgo O2 run.(*Right*) Cumulative distribution of the significance in the INTEGRAL/SPI-ACS instrument.

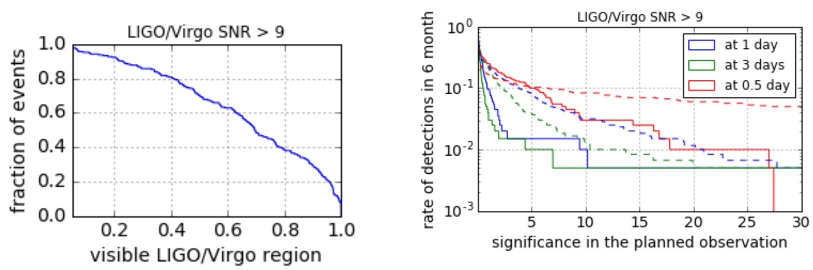


Figure 3. (*Left*) Cumulative distribution of the fraction of the LIGO/Virgo localization region accessible to INTEGRAL pointed follow-up observation in the LIGO/Virgo O2 run. (*Right*) Significance distribution on detected sources depending on time delay after the prompt emission. Dotted lines correspond to the model assuming realistic distribution of short GRB luminosities.

Results

Prompt – Passive follow-up

Choosing an isotropic sky distribution of our GW events, we show that in every case where the Earth is within the GRB emission cone, INTEGRAL detects prompt emission with significance at least 50 sigma. The rate of detection is 0.5 in the 6 months of O2 for GW alerts (SNR $\geq$ 9) and 0.1 in 6 months in the case of 4-sigma GW events (SNR = 11.5).

Afterglow – Instrument repointing

INTEGRAL can point only to a fraction of the GW localization region. For each event we compute the total localization probability within the observable region, and find that in 40% of the cases 80% of the localization is observed. However, if the complete available region is followed up every time, in total 80% of the true source locations are covered.

We find that the expected rate of 5 sigma detections is only about 0.01 events in 6 months of O2. We explore also another possibility, that 10% of the events launch much more energetic outflow, in agreement with luminosities observed in real short GRBs. In this case we expect about 0.1 events seen in 6 months.

We stress that the afterglow prediction is particularly sensitive to assumptions on rather uncertain source model, and we assume only one, yet realistic, option.

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