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High-energy follow-up studies of gravitational wave transient events

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Mergers of binary systems of compact objects are the most promising sources of gravitational waves (GWs) and are thought to be connected to some of the most energetic events in the universe: short Gamma Ray Bursts (GRBs). A definitive probe of this association is still missing and combined observations of gravitational and electromagnetic (EM) signals from these events are crucial to unveil the progenitors of short GRBs and study the physics of compact objects. We investigate the possibility of joint GW and EM observations of merging binary systems with the GW detectors Advanced LIGO and Advanced Virgo and with the Large Area Telescope (LAT) instrument on-board the *Fermi* γ-ray observatory.

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1. Introduction

The second-generation gravitational wave (GW) interferometers of the Advanced LIGO and Advanced Virgo project are currently undergoing major upgrades and will soon reach sensitivities sufficient to detect GWs directly for the first time, opening a new era in the multi-messenger investigations of the universe. One of the most promising sources for detection with Advanced LIGO and Advanced Virgo is the coalescence of binary systems of compact objects: binary neutron stars (NS-NS) and/or black holes (NS-BH, BH-BH). In fact, during the final stages of their inspiral phase, just before the merging of the two stars, these systems are very strong emitters of GWs in the frequency range covered by LIGO and Virgo ($\sim$ 10 Hz - 10 kHz). The merger of NS-NS and NS-BH systems could be also accompanied by electromagnetic (EM) emission. In particular, there are several evidences that short gamma-ray bursts (GRBs) originate from these mergers (see [1] and references therein). Short GRBs are intense flashes of γ rays lasting less than 2 seconds, sometimes accompanied by a long lasting weaker "afterglow" emission. They are thought to be powered by accretion onto the central compact object formed in the NS-NS or NS-BH system coalescence; the simultaneous detection of a short GRB and a GW signal will be a definitive proof of binary systems being the progenitors of these extremely energetic events. Furthermore, the detection of a coincident EM signal will increase the confidence of the GW detection of the merger, and provide complementary information (such as the precise sky localization or the distance to the source) on the event. Therefore, the EM follow-up of the merger of binary systems represents a key tool to better understand the physics underlying these extreme events and to unveil the nature of short GRB progenitors.

Among the various γ-ray instruments, the Large Area Telescope (LAT) on-board the *Fermi* satellite [2] is well suited for the EM follow-up of GW candidates for several reasons. First of all, its large field-of-view (FOV, $\sim$ 2.4 sr) can cover with few tiled exposures the large error boxes associated with the GW sky localizations provided by the alerts. Moreover, it can localize accurately the sources (the on-axis, 68% containment radius at 10 GeV is 0.8 deg), and disseminate these refined locations among other observatories for the follow-up of the GW events at other wavelengths.

Here we investigate the possibility for high energy follow-up of merging binary systems with the LAT. In particular, we focus on merging NS-NS systems, whose gravitational waveform is well modeled and understood. The work is organized as follows. In Sec. 2 we explain how we generate a sample of merging NS-NS systems. In Sec. 3 we present the procedure we use to estimate the GW detection rates and sky localization of the simulated events. In Sec. 4 we describe how we simulate the GRBs associated to the mergers and compare their EM emission with the LAT sensitivity. Finally, in Sec. 5 we present our results.

2. The merging NS-NS systems

The first step to construct a distribution of realistic NS-NS merging systems detectable by Advanced Virgo and Advanced LIGO is the generation of a sample of synthetic galaxies. We

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assume that Milky Way like galaxies dominate the Local Universe[1] and we use a constant galaxy density of 0.0116 Mpc^{-3}, that is the extrapolated density of Milky Way equivalent galaxies in space [3]. We give each galaxy a random, isotropic and uniform location in the sky and cut off the distribution at a distance of 250 Mpc, that is beyond the NS-NS range[2] of Advanced Virgo and Advanced LIGO in their final configuration [4]. Then we populate each galaxy with several merging NS-NS systems in accordance with the merger rate reported in [5], that we assume to have the same value for all galaxies; we consider an observing time of 1 year.

To populate the galaxies we extract merging NS-NS systems from a sample that we generate in the following way. We use the public synthetic database available at www.syntheticuniverse.org, developed by Dominik et al. 2012 [5]. They investigated the evolution of binary systems that leads to the formation of merging binary systems of compact objects (NS-NS, NS-BH and BH-BH) for a synthetic galaxy resembling the Milky Way. They use different population synthesis models, to account for the uncertainties associated with several evolutionary processes such as., i.e., stellar winds and consider two metallicities: $Z=Z_{\odot}$ and $Z=0.1\ Z_{\odot}$, where $Z_{\odot}$ is the solar metallicity. Here we focus on NS-NS systems with $Z=Z_{\odot}$ and generated with the so called "standard model - submodel A"; a more complete study including all other models and metallicity will be presented elsewhere.

For each binary system, the database provides the masses of the two compact objects, as well as an estimate of the merging time (sum of the time needed to form the two compact objects and the time for the two compact objects to coalesce). If the total time (merger time plus a randomly assigned starting time) is less that the age of the galaxy, assumed to be 10 Gyr, the system can be considered as a merging system and is included in our sample.

To reduce the statistical uncertainties, we generate 1000 realizations, each one for a 1 year observing period.

3. GW detections and sky localizations

We assign to each NS-NS merging system the same sky position (right ascension, declination and distance) of the host galaxy, and a random inclination of the orbital plane with respect to the line of sight. For simplicity, we assume that the systems are non-spinning.

For each merging NS-NS sytem, we simulate the expected GW inspiral signals, using the "TaylorT4" waveforms (see, e.g., [6]). After the GW signals have been simulated, we convolve them with the GW detector responses. We use the sensitivity curves of Advanced LIGO and Advanced Virgo reported in [4], describing five possible observing scenarios representing the evolving configuration and capability of Advanced LIGO and Advanced Virgo. In particular, we focus on two of these scenarios: the 2016-2017 scenario and the expected final "design" configuration, that will be achieved in 2019 and 2021 by Advanced LIGO and Advanced Virgo respectively. For the "design" configuration we use the noise power spectral density (PSD) curves reported in fig. 1 of [4]; for the 2016-2017 configuration we use the noise PSD curves in the middle of the ranges reported in [4].

[1] In this work we neglect the contribution of elliptical galaxies and galaxy clusters; a more detailed study will be presented elsewhere.

[2] Location and system orientation average distance.

The data obtained in this way are then analyzed with the matched filtering technique [7]. With this technique the data from all detectors are Wiener filtered with an array of theoretically modeled template waveforms (a "template bank"), constructed with different choices of the intrinsic parameters (e.g. the masses) of the binary systems. The output is an estimate of the signal to noise ratio (SNR) with respect to that template in that detector. If the signal results in a SNR above a given threshold in at least two detectors, with the same binary parameters and within approximately one light-travel time between detectors, it is considered as a GW candidate.

For simplicity, we construct template banks specifically designed to detect our simulated signals, e.g. with the same intrinsic parameters used for the simulated signals; the waveform we use is the "TaylorF2" (see [6]). We impose a network (two or three detectors) SNR (root sum square of the individuals SNR) threshold ρ_c=12, that corresponds to a false alarm rate (FAR) below 10^{-2} yr^{-1} [4].

For each GW candidate we then estimate the associated sky localization with BAYESTAR, a rapid Bayesian position reconstruction code that produces accurate probability sky maps in less than a minute after any NS-NS merger detection: this allows the prompt delivery of alerts to the astronomical community, enabling the EM follow-up of the GW events [8]. BAYESTAR is part of the LALSuite project, that comprises the routines for the analysis of GW data developed by the LIGO scientific collaboration and the Virgo collaboration.

We consider two cases: an optimistic one, in which all the interferometers are operating with a 100% duty cycle and a more realistic case, in which the GW detectors have an independent 80 % duty cycle (see for example [4]).

4. The simulated GRB sample

We assume that all the mergers of NS-NS systems are followed by a short GRB. We construct the light curve and spectrum of these GRBs using GRB 090510 as a template. This choice is motivated by the fact the GRB 090510 is the only short GRB to show emission up to GeV energies and, in particular, to show an extended emission (up to 200 s) at high energies (up to 4 GeV), as detected by the LAT [9]: this is a fundamental characteristic, since the overall time required to send GW alerts (a few minutes, see e.g. [8]) will not allow to follow-up the short GRBs themselves, but only their weaker afterglow emission.

The spectrum of the extended emission of GRB 090510 showed no significant evolution and it is well fitted by a power law with photon index α=-2.1 [10]; the light curve is well fitted by a power law with a decay index α_t=1.38 $\pm$ 0.07 [10]. We assume that the extended emission of the simulated GRBs has the same power law decay in time and the same spectral shape observed for GRB 090510. We then re-scale the observed flux of GRB 090510 to take into account the different total energy and distance of the source. In particular, we assume that the total EM energy emitted in γ rays during the prompt emission, $E_\gamma^{\mathrm{prompt}}$ is in the range observed for short GRBs, i.e. 10^{49} erg $\leq E_\gamma^{\mathrm{prompt}} \leq 10^{53}$ erg (see e.g. [1, 9]). Then, we assume that the fraction of energy emitted in γ rays during the afterglow is the same observed by LAT for GRB 090510, i.e. $\sim 0.5\ E_\gamma^{\mathrm{prompt}}$.

We also correct for the different inclination angle of the binary systems θ (corresponding to the angle of the GRB jet with respect to the line of sight). To do this, we consider a simplified model of a point source moving with a constant Lorentz factor Γ (see, for example, the model 1 in

[11]). Here we choose Γ=100, that is a reasonable value for the early afterglow emission; a more detailed analysis with different values of Γ will be presented elsewhere.

To verify if such simulated GRBs could be detectable by the LAT, we estimate the total integration time t_f required to have a fluence equal to the high energy LAT sensitivity corresponding to a GRB localization at 1-σ of 1 deg. This sensitivity has been estimated by extrapolating the one obtained with the Pass 7 reprocessed instrument response function of the LAT[3] to the energy range 0.1-300 GeV. We consider the LAT working in the survey mode.

5. Results

5.1 GW detections

Of the $\sim$ 18000 simulated NS-NS merging systems, about the 7.5 % (5.4 %) and 49.4 % (37.5 %) were GW detected with the 2016-2017 and design configuration respectively and considering a 100 % (80 %) independent duty cycle of each interferometer. The average GW detection rates are reported in Tab. 1. For comparison, we also report the values obtained by Aasi et al. 2013 [4] and Singer et al. 2014 [8], that have been obtained considering an 80 % duty cycle: it can be seen that all the values are consistent, within the error bars; the apparent discrepancy in the number of GW detections of NS-NS systems between our value and the one reported in Singer et al. 2014 [8] is a consequence of the higher merger rate they use.

To give an estimate of the accuracy of the sky localization of these GW events, we calculate the expected cumulative number of detections as a function of the areas, in deg^2, inside of the smallest 90 % confidence regions; these contours were constructed with the "water-filling" algorithm introduced in [8]. The results are shown in Fig. 1 and in Tab. 1. It can be seen that, with the design configuration and a 80 % duty cycle, $\sim$ 2 events per year could be GW detected with a sky localization $\leq$ 20 deg^2, small enough to allow for the LAT follow-up.

5.2 Joint EM and GW detections

Fig. 2 and Tab. 2 show the cumulative percentage of GRBs detectable by *Fermi*-LAT, as well as the cumulative percentage of events detectable both in EM and GW, as a function of the integration time t_f. It can be seen that, for an integration time of 1000 s, $\sim$ 3.6 % (1.0 %) of the mergers can be detected both in EM and GW for $E_\gamma^{prompt} = 10^{53}$ erg (10^{49} erg) and when considering the design configuration and a 100 % duty cycle of the interferometers: this corresponds to a rate of joint EM and GW detections of ~ 0.6 yr^{-1} (~ 0.2 yr^{-1}) .The estimated rates of EM detections should be considered as upper limits, since we are assuming that each NS-NS merger is accompanied by a GRB with emission at high energies.

It is worth to recall that these estimates have been obtained considering only NS-NS systems; a more complete analysis including NS-BH systems will be presented elsewhere. The inclusion of NS-BH systems is expected to increase the EM detection rate, due to the higher number of possible GRB progenitors and the larger explorable universe, since NS-BH mergers can be detected by GW interferometers up to larger distances with respect to NS-NS systems.

[3] http://www.slac.stanford.edu/exp/glast/groups/canda/archive/p7rep_v15/lat_Performance.htm

Configurations	Simulations	Number of NS-NS detections (yr^{-1})	% of NS-NS Localized within 5 deg^2	% of NS-NS Localized within 20 deg^2
2016-2017	Aasi et al. 2013 [4]	0.006-20	2	5-12
	Singer et al. 2014[a] [8]	1.5	2	8
	Sim., 80 % duty cycle	0.5 (0.01-1.7)	$2.3^{+1.2}_{-0.8}$	$7.9^{+1.9}_{-1.5}$
	Sim, 100 % duty cycle	0.7 (0.01 -2.3)	$2.8^{+1.0}_{-0.8}$	$10.8^{+1.8}_{-1.6}$
2019+ (design)	Aasi et al. 2013 [4]	0.2-200	3-8	8-28
	Sim., 80 % duty cycle	7.5 (0.05 - 12.4)	$7.6^{+0.7}_{-0.6}$	$27.6^{+1.1}_{-1.1}$
	Sim, 100 % duty cycle	8.8 (0.05 - 14.6)	$10.8^{+0.7}_{-0.6}$	$38.5^{+1.0}_{-1.0}$

[a]These estimates refer to the 2016 scenario.

Table 1: Expected GW detection rate and source localization for the 2016-2017 and the 2019+ (design) configurations, with an independent 80% duty cycle of each interferometer, as assumed in [4] and [8]. For the 2016-2017 configuration, our estimated number of NS-NS detections has been re-scaled to a 6-months observation period, to do a direct comparison with [4] and [8]. The range of GW detection rates reported in parenthesis has been estimated considering the highest range of NS-NS merger rates reported by Dominik et al. 2012, corresponding to model V12, submodels A and B [5].

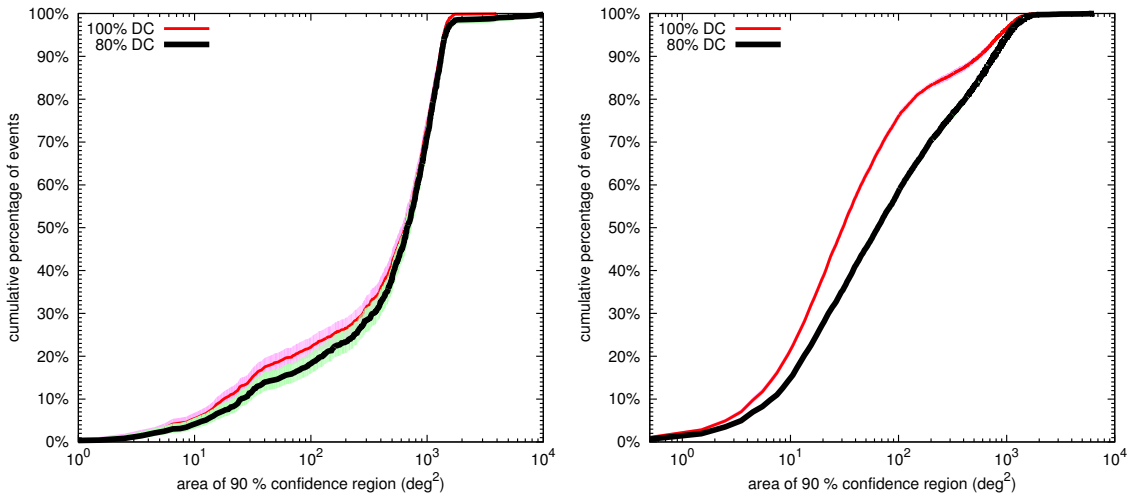

Figure 1: Cumulative histograms of sky localization areas in the 2016-2017 (left) and in the design (right) scenarios. The shadowed regions enclose the 95 % confidence intervals accounting for sampling errors, as computed from the quantiles of a beta distribution (see [12]).

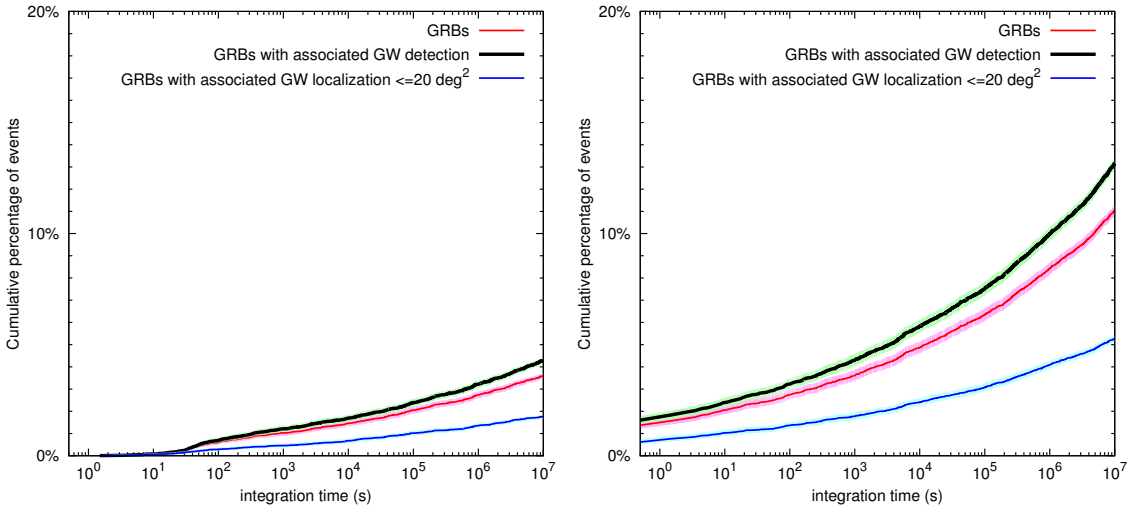

Figure 2: Left: cumulative histogram of the integration time needed for the simulated GRBs (in red), for the simulated GRBs with associated GW detection (in black) and with a sky localization ≤ 20 deg^2 (in blue) to be detected by the LAT. We assume $E_\gamma^{\rm prompt} = 10^{49}$ erg and, for the GW detections, we consider the design scenario and a 100 % duty cycle of each interferometer. Right: same as left, but we assume $E_\gamma^{\rm prompt} = 10^{53}$ erg.

Integration Time (s)	% of GRBs with EM detection	% of GRBs with EM and GW detections	% of GRBs with EM and GW detections, with GW localization within 20 deg^2
10	2.4 (0.1)	2.1 (0.1)	1.0 (0.1)
200	3.5 (0.9)	3.0 (0.8)	1.5 (0.3)
1000	4.3 (1.2)	3.6 (1.0)	1.8 (0.5)

Table 2: Expected percentages of EM and GW detections for the 2019+ (design) configuration, considering a 100 % duty cycle of the interferometers and assuming $E_\gamma^{\rm prompt}$=10^{53} erg (10^{49} erg).

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