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Searches for Gravitational Waves from Compact Binary Coalescences with LIGO and Virgo

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The Compact Binary Coalescence (CBC) analysis group of the LIGO-Virgo joint collaboration is looking for gravitational waves emitted during the coalescence of massive compact objects (neutron stars, black holes). The analysis is based on a matched filtering technique. Different template families are used: inspiral post-Newtonian templates for low-mass binaries (up to 35 $M_\odot$), inspiral-merger-ringdown templates for high-mass binaries (up to 100 $M_\odot$), and ringdown templates for perturbed massive black holes (up to 500 $M_\odot$). The CBC group pursues all-sky all-times searches and externally triggered searches for gravitational waves emitted by gamma-ray bursts progenitors.

1 Introduction

The LIGO-Virgo joint collaboration [1,2] aims to detect gravitational waves using a world wide network of laser interferometers. The Compact Binary Coalescence analysis group (CBC group) looks for gravitational-wave signals emitted during the coalescence of compact binary systems [3]. The waveform associated with such a gravitational-wave signal is described by theoretical models (see section 2), therefore a matched filtering technique [4,5] can be used for the analysis. The LIGO Scientific Collaboration has performed a two year-long data taking run (S5) from November 2005 to October 2007. The final five months of the S5 run were coincident with the Virgo first science run (VSR1) (May-October 2007). The CBC group is finalising the analysis of the S5-VSR1 data. A new S6-VSR2 run has started in July 2009 [6,7], its analysis just begins.

2 Match filtering and CBC searches

General relativity predicts that a compact binary system emits gravitational radiation while the orbits inspiral [3]. The two components (neutron stars, black holes) eventually coalesce. The coalescence can be decomposed in three main steps (Fig. 1): inspiral, merger and ringdown.
During the inspiral phase the waveform can be well modelled using the post-Newtonian (PN) approximation up to the frequency of the Innermost Stable Circular Orbit (ISCO) [3,8]. The time that an inspiral waveform spends inside the detection bandwidth (40Hz-2kHz) is of the order of several ten seconds for binary neutron stars and can be much less for black hole-neutron star or binary black holes. The frequency of the ISCO varies as the inverse of the total mass. Thus, for high mass systems the inspiral phase only covers the low frequency part of the detection bandwidth. Waveforms including the inspiral and merger can be obtained by numerical relativity. Approximated waveforms are also provided by the Effective One Body (EOB) method [9].

During the ringdown phase the excited final black hole releases energy by emitting gravitational radiation, the fundamental mode of which is an exponentionally damped sine function [10]. Expected waveforms are used as templates to perform a matched filter search [4,5]. The output of the matched filter is a signal-to-noise ratio (SNR) [5]. If the signal present in the data matches the template one obtains a SNR peak that is recorded as a trigger. For the templates used in our analyses the waveform depends on the two components masses of the binary searched (or the total mass and spin for a ringdown black hole). Therefore banks of several hundred or thousand templates are generated in order to cover the desired mass region [11,12]. The template family is chosen to optimize the sensitivity of the search to the requested mass region. The CBC group is performing three different all-sky all-times searches using three different template families:

- The "Low Mass CBC" search targets are binaries with total mass ranging from 2 to 35 solar masses ($M_\odot$). For such systems the inspiral phase covers most of the detection bandwidth, therefore PN templates are appropriate. These templates do not include spin but the effect of spin on the waveforms is negligeable for most of the parameter space [13].

- The "High Mass CBC" search covers binaries with total mass ranging from 25 to 100 $M_\odot$. In this mass region the whole coalescence may contribute to the SNR measured in the detection bandwidth. Therefore this search is carried out with inspiral-merger-ringdown templates. These waveforms are provided by the EOB method and are tuned to agree with the numerical relativity simulations. The sensitivity of a search can be expressed in term of the horizon distance, i.e. the distance at which an optimally oriented and located binary would produce a matched filter amplitude SNR [5] of 8. The horizon distance of a search using EOB templates at the LIGO design sensitivity is compared to the horizon distance that would be obtained with PN templates in Fig. 2. One can clearly see the benefits of the EOB templates in term of sensitivity for total masses above 30 $M_\odot$. Spin effect is not included in the EOB templates. The CBC group still needs to assess how this effect affects the performances of the High Mass search.

- The "Ringdown" search aims to detect black holes up to about 500 $M_\odot$ with templates that contain the ringdown part of the coalescence and include the spin of the black hole.

In addition to the matched filtering, the pipeline [12] used by all CBC searches requires the triggers to be found in coincidence (in mass and time) between at least two detectors. Moreover data quality cuts and signal-based vetoes are applied to reduce the rate of background triggers.

3 Recent analysis results

The Low Mass, High Mass, and Ringdown searches are being pursued over the data collected during S5-VSR1. The CBC group also runs externally triggered searches at the time of gamma-ray bursts (GRB), using PN templates. This section highlights some results already published from the Low Mass and GRB searches. Other analyses are still on going or under review.

3.1 Low Mass search

For the Low Mass CBC search the first 19 months of the LIGO S5 run have been analysed. The horizon distance is about 30 Mpc for binary neutron stars and reaches up to 150 Mpc for certain binary black holes. No signal was detected and upper limit results were published [13,14]. The results are reported in Tab. 1 for three canonical masses corresponding to instances of binary neutron stars, black hole-neutron star, or binary black holes systems. As shown in Tab. 1 the

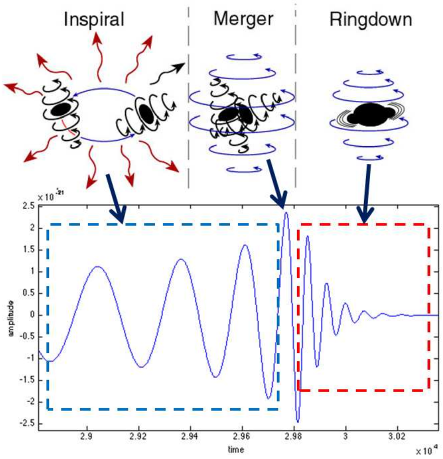

Figure 1: Coalescing compact binary system

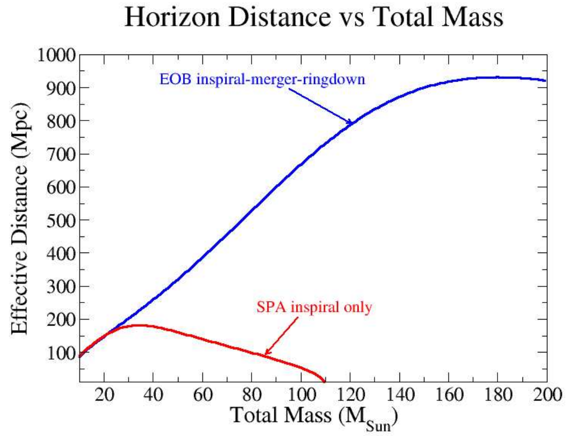

Figure 2: Horizon distance versus total mass for a search using EOB templates ("inspiral-merger-ringdown") and a search using PN templates ("SPA inspiral only"). The horizon is computed for equal mass systems with the LIGO design power spectral density.

Table 1: Low Mass search upper limits results for the first 19 months of S5 compared to optimistic and realistic astrophysical expected rates. The unit L_{10} is 10^{10} times the blue solar luminosity.

Component masses ($M_\odot$)	1.35/1.35	5.0/5.0	5.0/1.35
Search upper limit results ($yr^{-1}L_{10}^{-1}$)	1.4×10^{-2}	7.3×10^{-4}	3.6×10^{-3}
Optimistic expected rates ($yr^{-1}L_{10}^{-1}$)	5×10^{-4}	6×10^{-5}	6×10^{-5}
Realistic expected rates ($yr^{-1}L_{10}^{-1}$)	5×10^{-5}	4×10^{-7}	2×10^{-6}

upper limits are between one and two orders of magnitude above the optimistic astrophysical expected rates [15,16,17,18]. With the Advanced LIGO and Virgo detectors [6,7], the horizon distance should increase by a factor ~ 10 and the searched luminosity by a factor ~ 1000, allowing us to measure the rate of CBCs in the universe.
The last five months of the S5 run and the VSR1 run have been analysed jointly. This marks an important step for world wide network analysis, which is crucial to prepare for gravitational-wave astronomy. This analysis is under review.

3.2 GRB search

CBCs are possible progenitors for short GRBs of duration < 2s. During S5, 22 short GRBs were detected while at least two interferometers were operating. The CBC group has analysed the data in the period of time around these GRBs to look for gravitational-wave counterparts. An interesting case was GRB 070201 as its sky position error box overlapped with the spiral arms of the Andromeda galaxy (M31), at ~ 770 kpc. The two LIGO Hanford detectors operating at that time were sensitive up to 35.7 and 15.3 Mpc. An analysis was carried out by the CBC and Burst [19] groups leading to a null result [20] that excludes a CBC (with $1M_\odot < m_1 < 3M_\odot$ and $1M_\odot < m_2 < 40M_\odot$) as progenitor of the GRB in M31 at 99% confidence.

4 Perspectives for the S6-VSR2 run and the advanced detectors

The recent detectors upgrades and the start of the S6-VSR2 run mark an important step in the Enhanced LIGO and Virgo+ projects that aim to gain a factor 2-3 in sensitivity and about a factor 10 on the expected event rates. With the Advanced LIGO and Virgo detectors (for which the first data-taking runs are expected in ~ 2015), the sensitivity improvements (by a factor 10) should increase the event rates by ~ 1000. The expected event rates would then be in the order of a few tens of events per year for compact binary systems, making a detection very probable.

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