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SEARCHES FOR GRAVITATIONAL WAVES BURSTS IN THE FIRST JOINT RUN OF LIGO, GEO600 AND VIRGO

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Abstract. Gravitational wave burst analysis targets short ($< 1\,\mathrm{sec}$), generic or poorly modeled gravitational wave events. Such events could be caused by a wide range of sources like core-collapse of massive stars, neutron star excitations, black-hole mergers or gamma-ray bursts. We present the status of the searches for gravitational wave bursts in the first joint data from the global network of LIGO, GEO600 and Virgo interferometers, and the prospects for the upcoming data taking run.

1 Introduction

A worldwide network of interferometric gravitational wave (GW) detectors is now in operation. These are designed to observe gravitational radiation in a frequency band between a few dozen Hz up to a few kHz from astrophysical sources such as the coalescence of binary systems, core-collapse supernovae, rotating neutron stars as well as a stochastic background. The first Virgo science run (VSR1) took place from May 18^{th} up to October 1^{st} 2007 in coincidence with the end of the fifth LIGO science run (S5) (from November 2005 up to October 2007) (Robinet 2009).

2 Gravitational wave burst source

We consider here gravitational wave sources which may produce transient GW radiation with relativity short duration ($< 1\,\mathrm{s}$) or so called "burst". There are a few possible progenitors of such waveforms:

- Black hole (BH) – black hole, or black hole – neutron star (NS) mergers. Such events produce only a few cycles (number depending on mass of the system) in the detector sensitive band, and only in the BH-BH case does numerical relativity give good waveforms of the event. These mergers are the main model to explain the central engine for short gamma-ray bursts (GRBs) (Meszaros 2006), but no such binary has been observed yet. The merger rate is quite uncertain, it is expected to be $10 - 2000$ (including all types of mergers) per year with advanced GW detectors.

- Supernovae. Emission of GW radiation is expected during an asymmetric collapse of the star. The mode through which most of the GWs are radiated is quite uncertain. It could happen during the rebound of the iron core, or at a later stage when the proto neutron star is excited by the infalling matter. There are several instabilities scenarios that could drive this excitation (Ott 2009). Asymmetric supernovae are the main explanation for the origin of long GRB (Meszaros 2006).

- Neutron star oscillations. Relaxation in the crust of the neutron star can produce star-quakes, that results in a non spherically symmetric oscillations, which radiate GWs. This is the main model for Soft Gamma-ray repeaters (SGRs) and NS glitch observations.

- Cosmic string cusps and kinks. are more exotic sources, but are looked for as well (Abbott 2009a).

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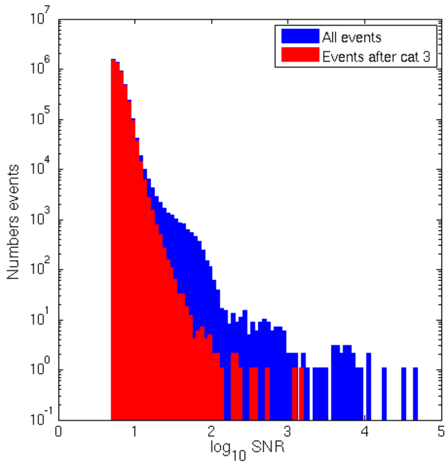

Fig. 1. Effect of data quality on Virgo triggers during VSR1. Histogram of the number of triggers as a function of decimal log of trigger SNR before (in blue) and after (in red) data quality cleaning.

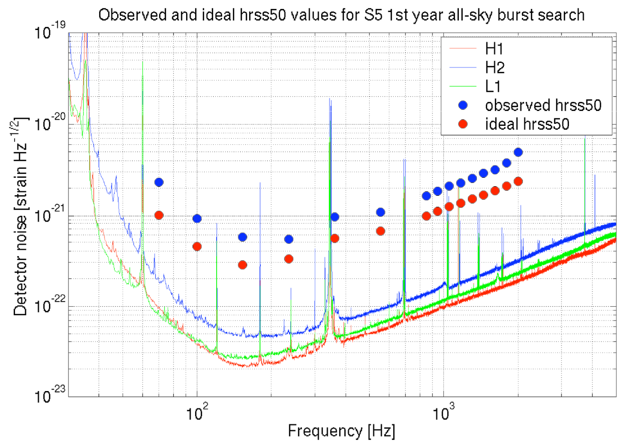

Fig. 2. Plotted are the noise floors of the three LIGO detectors, with overlaid the expected from gaussian noise (in red) and actual 50% sensitivity to GW (in blue).

3 GW bursts search methods

Given that most of the expected GW waveforms are poorly modeled, the search techniques have to be sensitive to a wide variety of waveforms, moreover they need to be robust against detector glitches that are unfortunately present in the data.

The detection algorithms are constructed in three main steps:

1. We make a decomposition of the data onto a time frequency map (using a wavelet transformation for instance), and look for excess power with regard to gaussian noise.

2. We use the information from the environmental channels to discriminate GW events from glitches in the detector.

3. We combine the data from the network of operational GW detectors.

The third step can be done in two different ways. Either after the first two steps, in a coincident analysis; or beforehand by making coherent combination of detector streams and then applying to them step 1 and 2.

The use of a network of detectors is a very powerful tool in GW data analysis. It is used for background estimation and to reduce the background event rate. It also allows a better time and sky coverage, because detectors do not have a 100% duty cycle nor a uniform antenna response. In the case where at least three detectors are operational, one can also reconstruct the source sky position through triangulation methods.

GW detectors have a large contribution of non gaussian noises. Some of those glitches are understood as environmental disturbances or instrumental noises. For others, no obvious explanation is found, and we rely on statistical correlations between auxiliary channels and GW triggers. In both cases triggers happening during noisy times are flagged and removed from the list of potential GW candidates. The result of this data cleaning for Virgo triggers during VSR1 can be seen in Fig. 1. It shows that a large number of glitches has been removed through this process.

Nonetheless a sizable amount of glitches pass these data quality tests and induce a time and frequency dependency of the trigger rate. This forces the detection cuts to be dependent on the frequency of the event. The sensitivities derived from the data are a factor between 2 and 3 (depending on the frequency) worse than what we would expect from a pure gaussian noise as shown on Fig. 2.

4 All sky untriggered search

The baseline search performed on S5/VSR1 data is an all sky untriggered search (Abbott 2009b,2009e). It looks for any kind of burst signal present in the data, using the method described above. In order to tune the search,

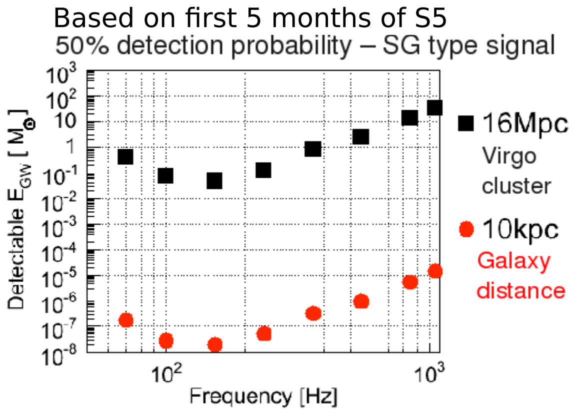

Fig. 3. Sensitivity to isotropically emitted GW energy as a function of signal frequency for two different source distances: 10 kpc and 16 Mpc.

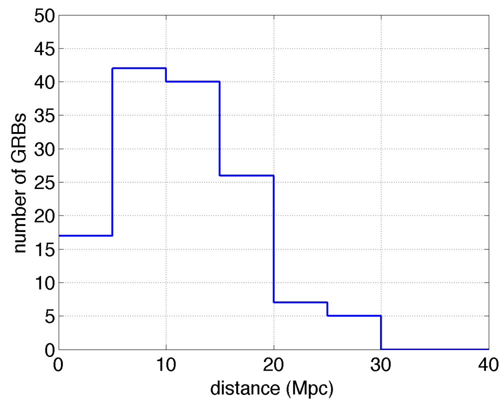

Fig. 4. Distribution of reachable distance for GRBs during S5/VSR1 in Mpc, assuming a standard candle of $0.01\,\mathrm{M_\odot c^2}$ emitted in GWs at 100 Hz.

the network background is estimated using time shifted data of the different detectors; while the detection efficiency is measured by repeatedly injecting simulated signals into the data and measuring the efficiency of retrieving these injections. Then the cuts are tuned to maximize the efficiency over a wide range of waveforms while keeping the background false alarm rate at 0.1 event per year.

The sensitivity estimate (50 % CL) are summarized in Fig. 3. The frequency dependence of these limits is due to the frequency dependence of the gaussian noise floor, and at the most sensitive point (around 150 Hz) the limit is $2 \times 10^{-8}\,\mathrm{M_\odot c^2}$ at 10 kpc, which scales with distance to $0.05\,\mathrm{M_\odot c^2}$ at 16 Mpc (distance to the Virgo cluster).

If we assume some model of emission we can convert this energy sensitivities into detection horizon for a given emission model. For supernovae using the models described in (Ott 2006) for $11\,\mathrm{M_\odot}$ the detection horizon is ~ 0.4 kpc and for $25\,\mathrm{M_\odot}$ it is ~ 16 kpc. This means that depending on the exact supernovae progenitor we can observe a small part or all of the Galaxy. For BH mergers assuming that roughly 3 % of the total mass is radiated into GWs (Pretorius 2009) for two $10\,\mathrm{M_\odot}$ black holes the reach is ~ 3 Mpc and for two $50\,\mathrm{M_\odot}$ it is ~ 100 Mpc, which means that the Virgo cluster is within reach for the merger of heavier black holes.

5 Interaction with electromagnetic observations

GW are not only searched by themselves but also in association of other astrophysical events. There are two ways of interacting with other astrophysical observations: triggering refined GW searches on astrophysical triggers or pointing GW candidates to astronomers for electromagnetic followup. The first way has become a mainstream analysis in the GW community, but the second possibility is currently in active development and should be operational in the near future.

5.1 External triggers

Using external triggers, that is astronomical observation of potential GW sources, provides two important pieces of information: a sky position and a time. The knowledge of the sky position reduces the coincidence time window between detectors, it also greatly simplify coherent analysis. The knowledge of the trigger time reduce the length of data to be analyzed, and thus lower the background level. The overall effect is that the sensitivity to GW is improved by a factor ~ 2. The triggers used so far are those related to GRBs using the GCN alerts, and major SGR outbursts.

In the GRB case, a search for GW counterparts of both long and short GRBs has been performed. During the last data run (S5/VSR1) 212 GRBs have been observed, for 70% of them at least two detectors where operational. The main result of this search is that the reachable distance for observing GW from a GRB is $D \sim 15\,\mathrm{Mpc}\sqrt{E^{\mathrm{iso}}_{\mathrm{GW}}/0.01\,\mathrm{M_\odot c^2}}$ as shown on Fig. 4. This result assumes that most of the GW radiation energy

$E_{\rm GW}^{\rm iso}$ is emitted isotropically and at a frequency around 100 Hz.

The expected number of GRBs within this horizon depends strongly on the population of GRBs that is considered. For long GRBs the expected rate is 10^{-6} evts/yr. Whereas for the under-luminous long GRBs, a subsample of the long GRB, the expected rate is 10^{-3} evts/yr (Abbott 2009c).

Among those GRBs, GRB 070201 has been singled out by a fast track analysis. It is a short GRB whose localization error box overlap the M31 galaxy, which is only 770 kpc away, thus being potentially a very nearby event. Due to its short nature, both an unmodeled and a specific binary coalescence search have been performed. At the time of this GRB only the two Hanford detectors were operational, and the null result exclude the hypothesis of a compact binary merger in M31 with a confidence greater than 99%. However this null result remains compatible with the possibility of an SGR in M31 or a compact merger in a galaxy behind M31 (Abbott 2008).

In the SGR case, the 2006 storm of SGR 1900+14 has been analyzed. The null result constrain the GW emission to $E_{\rm GW} < 10^4 E_{\rm EM}$, assuming an emission at 100 Hz. This limit although high, starts to constrain some theoretical models described in (Abbott 2009d).

5.2 Electromagnetic followup

Exploring GW candidates for further astronomical followup is a crucial issue for GW detection. An electromagnetic afterglow gives an independent confirmation that a real astrophysical event happened, and it also allows a further localization and study of the source of GWs.

Tools to perform these followups are being currently finalized. They require an online analysis at three sites, because interferometers are not pointing instruments and localization with a few degrees precision is obtained through triangulation.

These triggers are expected to be produced with a latency of dozens of minutes and send out to telescopes within a network of collaborators. The collaboration is in contact with robotic optical telescopes with large FOV (several square degrees), that are designed to find optical transients like ROTSE (Kanner 2008); and has also been awarded target of opportunity observation time on the Swift satellite.

6 Conclusions & Prospects

We have presented results from the all sky and externally triggered searches for unmodeled bursts in S5/VSR1 data, the upper limits derived start to be astrophysically relevant. During the next science run S6/VSR2 these analysis will be continued and we will also perform a rapid GW analysis leading to optical followup of candidates. Other multimessenger observations are in discussion with neutrino detectors and radio telescopes.

References

Abbott, B., et al. 2008, Implications for the Origin of GRB 070201 from LIGO. Observations *ApJ*, 681:1419

Abbott, B., et al. 2009, First LIGO search for gravitational wave bursts from cosmic (super)strings. *accepted in Phys. Rev. D*, arXiv/0904.4718

Abbott, B., et al. 2009, Search for gravitational-wave bursts in the first year of the fifth LIGO science run. *submitted to Phys. Rev. D*, arXiv/0905.0020

Abbott, B., et al. 2009, Search for gravitational-wave bursts associated with gamma-ray bursts using data from LIGO Science Run 5 and Virgo Science Run 1. *submitted to Phys. Rev. D*, arXiv/0908.3824

Abbott, B., et al. 2009, Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm. *ApJ*, 701:L68

Abbott, B., et al. 2009, *in preparation.*

Kanner, J., et al. 2008, LOOC UP: locating and observing optical counterparts to gravitational wave bursts. *Class. Quantum Grav.*, 25(18):184034

Meszaros, P. 2006, Gamma-ray bursts. *Rept Prog. Phys.*, 69:2259

Ott, C. D. 2006, A new mechanism for gravitational-wave emission in core-collapse supernovae. *Phys. Rev. Lett.*, 96(20):201102

Ott, C. D. 2009, Probing the core-collapse supernova mechanism with gravitational waves. arxiv/0905.2797

Pretorius, F. 2009, *Physics of Relativistic Objects in Compact Binaries: from Birth to Coalescence*, volume 359 of *Astrophysics and Space Science Library*, chapter Binary Black Hole Coalescence. arxiv/0710.1338

Robinet, F. 2009, *in this volume*