The joint search for gravitational wave and low energy neutrino signals from core-collapse supernovae: methodology and status report

M B Gromov$^{1,2}$ and C Casentini$^{3,4}$

1 Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics, 119234 Moscow, Russia
2 Lomonosov Moscow State University, Faculty of Physics, 119234 Moscow, Russia
3 Università degli Studi di Roma "Tor Vergata", Dipartimento di Fisica, Via della Ricerca Scientifica 1, 00133 Roma, Italy
4 INFN, Sezione di Roma Tor Vergata, Via della Ricerca Scientifica 1, 00133 Roma, Italy

E-mail: gromov@physics.msu.ru, Claudio.Casentini@roma2.infn.it

Abstract. The detection of gravitational waves opens a new era in physics. Now it’s possible to observe the Universe using a fundamentally new way. Gravitational waves potentially permit getting insight into the physics of Core-Collapse Supernovae (CCSNe). However, due to significant uncertainties on the theoretical models of gravitational wave emission associated with CCSNe, benefits may come from multi-messenger observations of CCSNe. Such benefits include increased confidence in detection, extending the astrophysical reach of the detectors and allowing deeper understanding of the nature of the phenomenon. Fortunately, CCSNe have a neutrino signature confirmed by the observation of SN1987A. The gravitational and neutrino signals propagate with the speed of light and without significant interaction with interstellar matter. So that they must reach an observer on the Earth almost simultaneously. These facts open a way to search for the correlation between the signals. However, this method is limited by the sensitivity of modern neutrino detectors that allow to observe CCSNe only in the Local Group of galaxies. The methodology and status of a proposed joint search for the correlation signals are presented here.

A number of recent studies that are reviewed in [1] predict gravitational wave (GW) emission during supernova explosion. New instruments such as aLIGO and aVIRGO [2] provide an opportunity to take a glance not only at the phenomena in the depths of the Universe [3], but in very compact objects like supernovae. It is also useful because any new facts will give information about gravitational waves itself. And low energy neutrinos from supernova explosion [4, 5, 6, 7, 8] serve as a mark of the process. The main problem of supernova observation is the event rate of this type. It’s about a few events per a century in Milky Way, where modern detectors can register neutrinos and gravitational waves. The multi-messenger astronomy may increase this range several times as it will be shown below.

According to [1] the most studied class of models describing the GW generation in supernovae is based on the rotating core collapse and core bounce mechanism. The corresponding analytical picture presumes existence of rapid precollapse rotation in combination with angular momentum conservation during collapse. It leads to rapidly time-varying quadrupole deformation of the collapsing and bouncing core. Hence the collapse must be asymmetrical. Also the class of models
under consideration predicts a few characteristic properties of the gravitational signal [1, 9]. It should have a duration from a few milliseconds to several seconds. The GW energy $\Delta E_{GW}$ is released during the collapse is about $10^{-10} - 10^{-4} M_\odot$ in the frequency band of $10^2 - 10^3$ Hz. The characteristic amplitude $h_c$ is defined with the parametric formula [10]:

$$h_c \sim 2.7 \times 10^{-20} \left( \frac{\Delta E_{GW}}{M_\odot c^2} \right)^{\frac{1}{2}} \left( \frac{1 \text{ kHz}}{f_c} \right)^{\frac{1}{2}} \left( \frac{10 \text{ Mpc}}{r_0} \right),$$

where $r_0$ is a distance to the supernova and $f_c$ is a GW frequency.

The research was initiated with the article [11]. The working group was created in 2014 and it originally included 5 experiments, namely Advanced LIGO, Advanced VIRGO, IceCube, LVD, Borexino. KamLAND-Zen joined this year.

The first step of such analysis is to account for the single detector its duty cycle and hence calculate the common observation time of the network of involved detectors or any of the resulting subnetworks. All physical data of various detectors is considered with minimal possible constraints because the real supernova signal may be smaller than some kind of noise. The joint analysis allows to extract this faint signal.

The basis of the search is a burst selection taking into account as a main parameter the probability that the examined burst is just a background superposition. This probability is described in terms of the False Alarm Rate (FAR [2, 9] or the Imitation Frequency [12, 13]). It is a number of accidental background fluctuations above the detection threshold per year. The joint FAR is also applied and it represents a number of accidental coincidence of detector signals in the network. The joint FAR $R_{joint}$ is given by

$$R_{joint} = \prod_{i=1}^{N} R_i \times (2t_{coin})^{N-1},$$

where $R_i$ is the selected FAR of the $i$ detector, $t_{coin}$ is a coincidence window between GW and $\nu$ signals in which the correlation is looked for. In a conservative approach $t_{coin} = 10$ s, whereas according to the article [14] the coincidence window should be in order of tens ms. The factor "$2" appears due to unknown time order of signals.

The capability of the joint analysis can be easily illustrated with the joint FAR. The detector network consists of the GW and $\nu$ parts. Let’s choose the joint FAR of 1 burst/1000 yr and the GW subnetwork FAR of 1 signal/1 month.

$$R_{joint} = 1 \text{ burst/1000 yr} = R_{GW} \times R_{LVD} \times R_{IceCube} \times R_{Bx} \times (2t_{coin})^3.$$  

Assuming the same FAR per each $\nu$ detector one gets $R_{Bx} \sim 2 \times 10^{-3} \text{ Hz} \sim 1 \text{ burst/10 min}$. The obtained value is large in comparison with the selected joint FAR. If there is only one detector in the global network it’s necessary to stay at very low value of the FAR in order to be statistically significant. For example, the value equals 1 burst/100 yr in the LVD paper [12]. As a result, the network may expand the area of observation beyond the Milky Way.

Due to lack of facts about the core-collapse mechanism the unbiased search should be applied as much as possible. There are two possible types of the joint analysis. The first one is a model independent search for correlations between gravitational waves and neutrino bursts of any flavour. The analysis is ongoing. The second approach is a search for correlations between gravitational waves and inverse $\beta$-decay events. The first attempt of such an analysis has been made by KamLAND [15].

The GW event selection in the current search is performed using the coherent waveburst analysis (cWB) [16]. It’s a wavelet based data processing designed to extract unmodelled GW burst signals. In turn the neutrino burst selection is exploited using the LVD technique [12]. Also
the LVD online identification [13] may be used to speed up and simplify the analysis despite the fact that this approach is rougher and not as accurate as the previous one. Both selection algorithms guarantee 100% efficiency of the LVD trigger up to 25 kpc of the source. The procedure of the joint search is shown as a flowchart in Fig. 1.

Figure 1. A block diagram of the search strategy.

Currently the coincidence search program is under development and testing. For this purpose archived data (2005–2015) is planned to be used. To verify the technique and tools a simulation work is ongoing. It’s also useful to evaluate the efficiency of the search for correlations depending on the distance to a supernova and the number of detectors in the network. These assessments and tests can be done by inserting the generated signals to real data. But there is a penalty in this case. It’s necessary to use some supernova models hence the efficiency is model-dependent. The first approach is reproduction of the SN1987A signal using the results of one of the last analyses [17]. After that it is planned to implement the following three models as reference ones: 1) the Lawrence-Livermore model as a toy model [18]; 2) the conservative (pessimistic) scenario producing the low neutrino flux [19]; 3) the (optimistic) scenario of a rare supernova, that produces lots of neutrinos with rising energy [20].

Acknowledgments
The authors thank the collaborators in this work, namely Erik Katsavounidis, Giulia Pagliaroli, Viviana Fafone, Walter Fulgione, Lutz Koepeke, Gemma Testera, Virginia Re, Christian Ott, Carlo Vigorito, Kate Scholberg and Lindley Winslow, for useful discussions and guidance.

References
[1] Ott C D 2009 Class. Quant. Grav. 26 063001 (Preprint 0809.0695v2)
[2] Abbott B P et al. (LIGO and Virgo Collaborations) 2016 Living Rev. Relativity 19 (Preprint 1304.0670v3)
[3] Abbott B P et al. (LIGO and Virgo Collaborations) 2016 Phys. Rev. Lett. 116 061102 URL PRL website
[4] Hirata K et al. 1987 Phys. Rev. Lett. 58 1490-93 URL PRL website
[5] Bionta R M et al. 1987 Phys. Rev. Lett. 58 1494-96 URL PRL website
[6] Alekseev E N et al. 1987 JETP Lett. 45 589-92 URL JETP Lett. website
[7] Aglietta M et al. 1987 Europhys. Lett. 3 1315-20 URL IOP website
[8] Dadykin V L et al. 1987 JETP Lett. 45 593-955 URL JETP Lett. website
[9] Casentini C 2016 J. Phys.: Conf. Series 718 072001 URL IOP website
[10] Castellani V 1985 Fondamenti di Astrofisica Stellare (Zanichelli Editore)
[11] Leonor I et al. 2010 Class. Quant. Grav. 27 084019 URL IOP website (Preprint 1002.1511v1)
[12] Agafonova N Y et al. (LVD Collaboration) 2015 ApJ 802 47 (Preprint 1411.1709v2)
[13] Agafonova N Y et al. (LVD Collaboration) 2008 Astropart. Phys. 28 516–22 (Preprint 0710.0259v1)
[14] Pagliaroli G et al. 2009 Phys. Rev. Lett. 103 031102 (Preprint 0903.1191v1)
[15] Gando A et al. (KamLAND Collaboration) 2016 (Preprint 1606.07155v1)
[16] Klimenko S et al. 2008 Class. Quant. Grav. 25 114029 URL IOP website (Preprint 0802.3232v2)
[17] Pagliaroli G et al. 2009 Astropart. Phys. 31 163–76 (Preprint 0810.0466v1)
[18] Totani T et al. 1998 Astrophys. J. 496 216–25 (Preprint astro-ph/971023v1)
[19] Hüdepohl L et al. 2010 Phys. Rev. Lett. 104 251101 URL PRL website
[20] Sumiyoshi K et al. 2007 Astrophys. J. 667 382–94 URL IOP website (Preprint 0706.3762v1)