

Methodology of the joint search for Gravitational Wave and Low Energy Neutrino signals from Core-Collapse Supernovae

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Abstract. Core-Collapse Supernovae (CCSNe) have a neutrino (ν) signature confirmed by SN 1987A and are potential sources of Gravitational Waves (GWs). ν s and GWs coming from these sources will reach the observer almost simultaneously and without significant interaction with interstellar matter. The expected GW signals are in the range of the upcoming advanced detectors for galactic neighborhood events. However, there are still significant uncertainties on the theoretical model of the emission. A joint search of coincident ν s and GWs from these sources would bring valuable information from the inner core of the collapsing star and would enhance the detection of the so-called Silent Supernovae. Recently, a project for a joint search involving GW interferometers and ν detectors has started. In this paper we discuss about the principal GW theoretical models of emission, and we present a methodological study of the joint search project between GW and ν .

1. Introduction

The current model of the Universe is like a puzzle with many cards missing. Photons are the messengers that describe almost all we know about the Universe. We are investigating the sky at all accessible wavelengths of the electromagnetic spectrum. However, a relevant fraction of the Universe should be composed of matter that is not emitting photons, or whose emission should be covered by cold matter (i.e. gas or dust).

It is obvious that we need another probe not related to electromagnetic emission. The detection of gravitational waves and neutrinos seems one of the most promising discovery tool for the future investigation of the Universe, shedding light on physical phenomena such as the explosion mechanism of Core-collapse SuperNovae (CCSNe).

2. Scientific case

In this section we provide a quick overview of a CCSN and how this kind of events could generate gravitational signature. Core collapse Supernovae are among the most energetic events observable in the electromagnetic spectrum. They result from the rapid collapse and violent explosion of a massive star and in few seconds they can irradiates $\sim 10^{53}$ erg.



Prior to becoming a supernova, an evolved massive star is organized in the manner of an onion, with layers of different elements undergoing fusion. The outermost layer consists of hydrogen, followed by helium, carbon, oxygen, and so forth until the inert nickel-iron core in which any fusion process produces no net energy output. Due to the lack of energy, hydrostatic equilibrium is broken and a cataclysmic implosion takes place in seconds, in which the core reaches an inward velocity of up to 23% of the speed of light and temperatures of up to 100 billion kelvins. Neutrons and neutrinos are formed via reversed beta-decay, releasing about 10^{46} J in a ten-second burst. The collapse is halted by neutron degeneracy, causing the implosion to rebound. The energy of this expanding shock wave together with the neutrino heating is sufficient to accelerate the surrounding stellar material to escape velocity, forming a supernova explosion. Depending on the initial size of the star, the remnants of the core form a neutron star or a black hole.

3. Physical scenario

Modelling the stellar core-collapse and post bounce evolution of the SN core is a multi-scale and multi-physics problem. In the modelling phase we have to take into account lengthscales from thousands of kilometers (typical of the pre-SN stellar core) to meters (typical of the small scale turbulence). Furthermore, a realistic model should include general relativity, general relativistic magneto hydrodynamic, neutrino interactions and other important physical interaction mechanisms. None of the currently published numerical models live up to above standards. However, in this kind of sources, we expect to have gravitational emission only if an asymmetrical collapse of the core occurs: primarily from rotating collapse and bounce of the iron core, non-axisymmetric rotational instabilities and proto-neutron star (PNS) pulsation. In addition, an-isotropic neutrino emission, global pre-collapse asymmetries in the iron core and surrounding burning shells, aspherical mass ejection and other mechanism that provide the appearance of a quadrupole mass-moment during the collapse may contribute to the overall GW signature. A non-complete list of models for the emission mechanisms includes [3][4]:

- Rotating core collapse and core bounce;
- Rotational 3D instabilities;
- PNS pulsations.

We can analyze briefly the most studied of the above mechanisms, the rotating core collapse and core bounce model. Rapid pre-collapse rotation, in combination with angular momentum conservation leads to an elongation and contraction of the collapsing core. The core results separated in a subsonically homologously contracting inner core and a supersonically infalling outer core. The responsible for the GW burst is the inner core. The simulations allowed the identification of three types of gravitational signals (Fig.1) that may be associated with distinct dynamics for the collapse and rebound:

- Type 1. For models subjected to rebound governed by the freezing of the parameters of the nuclear equation of state (EOS) at nuclear density. Their waveforms exhibit one pronounced large spike at bounce and then show a gradually damped ring down;
- Type 2. For models significantly affected by the rotation and subjected to a rebound of the core dominated by centrifugal forces. Their dynamics exhibit multiple bounces, which is reflected in the waveform by distinct signal peaks associated with each bounce.
- Type 3. For models characterized by fast collapse, extremely small masses of the homologously collapsing inner core, low-amplitude GW emission and a subdominant negative spike in the waveform associated with bounce.

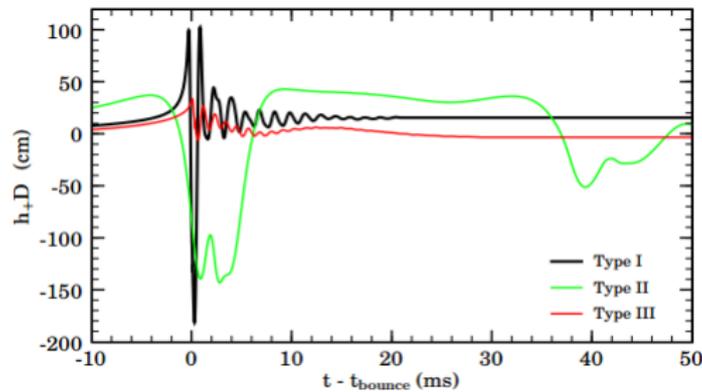


Figure 1 The three types of GW emission as reported in [3].

From recent simulations it is found that the signal due to gravitational collapse of rotating object has a typical shape of the Type 1 above. The other two models are almost always absent. It was also demonstrated that the collapse in rotation and the dynamics of the bounce and resulting GW burst signals depend primarily on the central angular velocity in the pre-collapse phase.

The signal can last from a few milliseconds to a few seconds [5], and the energy converted into GWs before the explosion is of the order of $10^{-10} - 10^{-4} M_{\odot}$. A typical supernova explosion event should generate a GW signal in the $10^2 - 10^3$ Hz frequency band, with a characteristic amplitude that depends on the local amount of energy released in gravitational waves. This quantity is given by [2]:

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

In a SN explosion, 90% of the energy is conveyed in the neutrino channel. Some neutrinos from a core collapse have already been recognized: 19 neutrinos from SN 1987A [1].

CCSNe and ν s are emitted, with a time delay ranging from 1 s to 20 s (as reported in [5]), in the inner regions of the star, the core of the PNS, which cannot be studied electromagnetically, hence they uniquely provide information on the internal mechanisms in place during a CCSN. From neutrinos we could be able to extract information about the equation of state (EOS) of the PNS and from GWs information on the multi-dimensional dynamics of the collapse, such as deformation of the nucleus. Conflating data from GW and neutrino observatories, in a joint analysis allows to find any coincidence between these.

Concerning the number of SN events, the expected rate in our Galaxy and the Local Group of galaxies (up to the distances of the order of 300 kpc) is rather low and probably less than 1 event per two decades.

4. Search proposal and strategy

We look for coincident events from GW and Supernova ν experiments in order to get insights into the physics of the core collapse. The search pipeline will be previously tested on archival ν and GW data before being used on incoming new data. The project currently involves three ν experiments but it is open to other interested experiments.

Fig.2 shows how the analysis pipeline setup is organized in two main stages: the background characterization and the study of the detection efficiency to incoming signals. The former is performed by analyzing the statistical distribution of accidental coincidences. The latter is pursued by injecting simulated signals into the datasets and checking the ability of the pipeline to retrieve them. The data coming from the different communities could be combined in many different ways. In the following we describe the main steps to design a joint analysis between a network of heterogeneous detectors.

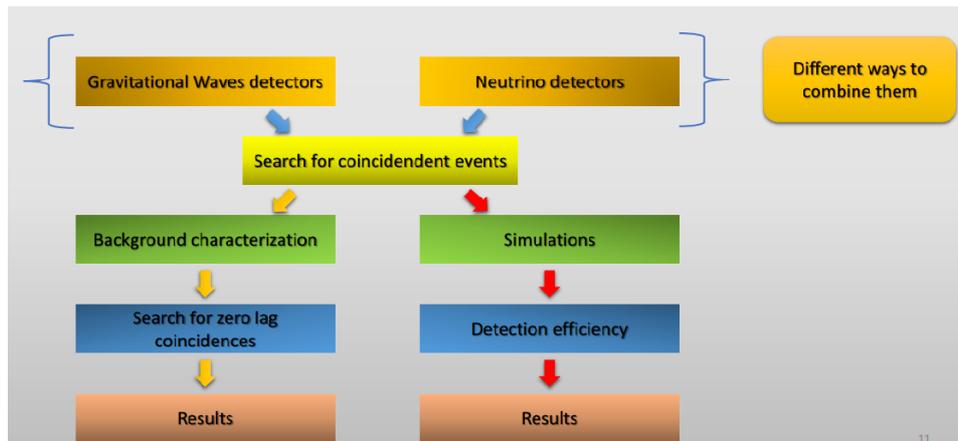


Figure 2 Scheme of the analysis pipeline setup.

One of the most important steps for a joint analysis, is to account for the single detector duty cycle and hence calculate the common observation time of the network of involved detectors or of any of the resulting subnetworks. The duty cycle is the percentage of time in which one detector is active.

We need also to set a global False Alarm Rate (R_{joint}) when searching for coincidences. This value represents a threshold that marks significant events for further investigation. In a Poisson process, this rate is expressed as: $R_{joint} = (R_1 \times R_2 \times \dots \times R_N) \times (2t_{coin})^{N-1}$, where R_i is the selected event rate of the i -th detector, t_{coin} in the time coincidence window considered. The factor two in front of the coincidence window t_{coin} accounts for the fact that coincidence searches generally impose the relative timing of a GW and neutrino event to be within t_{coin} , but not in a specific order.

To estimate the significance of a candidate GW- ν event, we need to characterize the statistical distribution of the accidental coincidences. To create this distribution, we apply unphysical delays between the detectors data streams of the network, in order to remove all the possibly true astrophysical signals. In our analysis we choose to shift the neutrino detector datasets with respect to the GW dataset by a time interval greater than the physical delay between the neutrino and GW emission. This delay may range between 1s and 20s. Coincident triggers are selected in the shifted datasets and their distribution as function of the physical or statistical quantity of interest (energy, significance) describes the number of accidental coincidences expected. The ratio of the number of fake coincidences to the total time of the background collected in the shift analysis represents the rate of accidentals and we study it as a function of a physical quantity of interest per each detector of the network. This part of the analysis will be performed using the coherent waveburst pipeline (cWB) [6] [7], a wavelet based data analysis tool designed to search for unmodelled GW burst signals.

After the background characterization, we look for coincident events in the un-shifted datasets looking for any common signal exceeding the fixed threshold. In case no result is found, we can set an upper limit on the rate of events assuming a given confidence level [8].

We also have to investigate how well our searching algorithm is able to find a true signal inside the stream of data. We will use simulated GW waveforms and neutrino fluxes from different models, i.e. [9] [10]. Then, we will inject in the GW detectors dataset the simulated GW waveforms and in the ν detectors dataset the simulated signal fluxes and we will estimate the detection efficiency as the percentage of the injected signal that we will find in the output.

5. Involved experiments

In the context of this project, we are working with the data from the three GW detectors Advanced LIGO (aLIGO) [11] and Advanced Virgo (AdV) [12], and three neutrino detectors: Borexino [13], Large Volume Detector (LVD) [14], and IceCube [15]. A general overview of detectors is provided in the following.

Advanced LIGO and Advanced Virgo are interferometric GW detector. AdV is currently completing its upgrade, while the aLIGO detectors were recently upgraded and have been taking data since mid-September 2015.

Advanced LIGO is composed by two interferometers with 4km long arms, located in Hanford, Washington, USA and in Livingston, Louisiana, USA. The Virgo detector, is a 3 km long interferometer (operated by an

Italian French collaboration) located in Cascina (Pi), Italy. These detectors are designed to be power-recycled Michelson interferometers. In their first generation design, these detectors were sensitive to h values of the amplitude of $\sim 10^{-22}$. After the upgrade, the performed improvement will be of one order of magnitude over all the detection bandwidth.

LVD is a scintillator detector, operated by the Italian Institute of Nuclear Physics (INFN) and the Russian Institute for Nuclear Research of Moscow (INR), that can detect both charged current and neutral current interactions. LVD is mainly dedicated to the detection of neutrino bursts from stellar collapses occurring in our galaxy or in the Magellanic Clouds. One of its most important features is the possibility to detect neutrinos in several channels, allowing a more careful study of the energy characteristics of the neutrino burst from collapsing stars [16, 17]. Borexino is a scintillator detector born to study low energy (sub MeV) solar neutrinos, located in the Laboratori Nazionali del Gran Sasso. The primary aim of the experiment is to make a precise measurement of the ${}^7\text{Be}$ neutrino flux from the sun and comparing it to the Standard solar model prediction. It may also be able to detect neutrinos from supernovae in our galaxy. The IceCube Neutrino Observatory is a neutrino telescope composed of thousands of sensors distributed over a cubic kilometer volume under the Antarctic ice. It is designed to look for point sources of neutrinos in the TeV range. Despite the fact that individual neutrinos expected from supernovae have energies well below the IceCube energy cutoff, IceCube could detect a local supernova. All these detectors are part of SNEWS [18].

6. Benefits of the joint analysis

Searching coincidences of GWs and vs will lead to a deeper understanding of the physics inside the core of the source. A distant event with low statistical significance in GW could achieve higher detection confidence from joint search requirements. For galactic silent CCSNe, a coincidence with GW would help constraining the physical models governing the dynamics inside the core. Requiring coincidence with gravitational triggers would allow GW and ν detectors to operate at lower thresholds, relaxing criteria for detection. The guideline for this is to fix a false alarm rate (FAR) of the search so that the single searches thresholds can be modified while keeping FAR constant. A joint FAR of the order of 1/1000 years can be typically required. In this context, if, for example, the ν threshold is lowered to the level of 1 event per day, the improvement for GW and ν searches that we would get are reported in Fig.3. As we can see, lowering the ν threshold would correspondingly lead to an increase of the probability to detect neutrinos from distant supernovae and to a 10-20% gain in GW sensitivity (blue solid line with respect to the red dashed line), following [19]:

$$E_{\text{GW}} = \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\text{rSS}}^2 \quad (2)$$

In Equation (2) D is the distance from the source expressed in kpc, f_0 is the signal frequency and h_{rSS} is the signal amplitude at the GW detector.

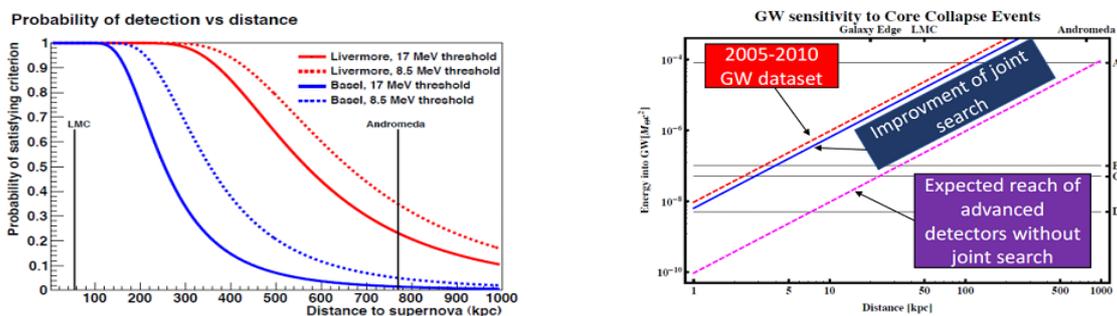


Figure 3 Benefits of the joint search. In the left panel there is the gain in the probability of detect neutrinos from distant CCSNe. In the right panel there is the gain in GW sensitivity. These two plot are from the internal proposal “Neutrinos meets Gravitational Waves: Preparing for the Next-Nearby Core-Collapse Supernova”.

7. Conclusions

Purpose of this paper is to expose the methodologies to be considered in the framework of the search for coincident gravitational wave and neutrino signals from Supernovae. A lot of work remains to be done in this context since this effort is at its beginnings and it involves different scientific communities. For the time being studies aimed to setting up methodologies and preparing the pipeline for the new data from advanced interferometers. The future steps will address more in depth the design of the search and its tuning.

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References

- [1] Hirata *et al* 1987 *Phys. Rev. Lett.* **58** 1490
- [2] Castellani V 1985 *Fondamenti di Astrofisica Stellare*, Zanichelli Editore
- [3] Ott C 2009 *Class. Quantum Grav.* **26** 063001
- [4] Kotake K 2013 *C. R. Physique* **14** 318-351
- [5] Pagliaroli G *et al.* 2009 *Phys. Rev. Lett.* **103** 031102
- [6] Sutton P J 2009 *Class. Quant. Grav.* **26** 245007
- [7] Klimenko *et al* 2008 *Class. Quant. Grav.* **25** 114029
- [8] <https://atlas3.atlas.aei.uni-hannover.de/~waveburst/doc/cwb/man/>
- [9] Ott C *et al* 2006 *Phys. Rev. Lett.* **96** 201102
- [10] Totani *et al* 1998 *ApJ* **496** 216
- [11] Abbott B and LIGO Scientific Collaboration 2009 *Rept. Prog. Phys.* **72** 076901
- [12] Accadia T *et al* 2012 *JINST* **7** P03012
- [13] Cadonati L, Calaprice F P and Chen M C 2002 *Astropart. Phys.* **16** 361
- [14] Agafonova N Y *et al* 2008 *Astropart. Phys.* **28** 516
- [15] Halzen F, Jacobsen J E and Zas E 1996 *Phys. Rev. D* **53**, 7359
- [16] Giusti P 2014 *Pontifical Academy of Sciences Scripta Varia* **119** Vatican City
- [17] Fulgione W 2006 *Mem. S. A. It. Suppl.* **9** 388
- [18] <http://snews.bnl.gov/>.
- [19] Abbott B and LIGO Scientific Collaboration 2007 *Class. Quantum Grav.* **24** 5343