

Methodological studies on the search for Gravitational Waves and Neutrinos from Type II Supernovae

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Abstract. Type II SNe, also called Core-collapse SuperNovae have a neutrino (ν) emission, as confirmed by SN 1987A, and are also potential sources of gravitational waves. Neutrinos and gravitational waves from these sources reach Earth almost contemporaneously and without relevant interaction with stellar matter and interstellar medium. The upcoming advanced gravitational interferometers would be sensitive enough to detect gravitational waves signals from close galactic Core-collapse SuperNovae events. Nevertheless, significant uncertainties on theoretical models of emission remain. A joint search of coincident low energy neutrinos and gravitational waves events 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 gravitational wave interferometers and neutrino detectors has started. We discuss the benefits of a joint search and the status of the search project.

1. Introduction

The current model of the Universe is like a puzzle with many pieces 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 does not emitting photons, or whose emission is dominated by the cold matter one (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 the most promising discovery tool for the future investigation of the Universe, shedding light on physical phenomena that have been theorized only, such as the explosion mechanism of Core-collapse SuperNovae (CCSNe).

2. Scientific case and physical scenario

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, since the star irradiates 10^{53} erg in few seconds. The most brilliant supernovae in the Universe can exceed the brightness that of their host galaxies. In these sources the kiln of the gravitational radiation is the collapsing core and Type II supernovae results from the rapid



collapse and violent explosion of a massive star. Stars generate energy by nuclear fusion of elements: this energy together with the degeneracy pressure of electrons balances the force of gravity and prevents the star from collapsing. Massive stars can fuse elements with atomic number greater than hydrogen and helium and result in a core of iron and nickel (see Table 1) [2].

<i>Process</i>	<i>Main products</i>	<i>Temperature (K)</i>	<i>Duration (yr)</i>
<i>Hydrogen burning</i>	He	7×10^7	10^7
<i>Helium burning</i>	C, O	2×10^8	10^6
<i>Carbon burning</i>	Ne, Na, Mg, Al	8×10^8	10^3
<i>Neon burning</i>	O, Mg	1.6×10^9	3
<i>Oxygen burning</i>	Si, S, Ar, Ca	1.8×10^9	0.3
<i>Silicon burning</i>	Ni, Fe	2.5×10^9	5 days

Table 1 Overview of life stages of a massive star.

Therefore, 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. Fusion of iron or nickel produces no net energy output leaving the nickel-iron core inert. Due to the lack of energy output outward pressure, equilibrium is broken. A cataclysmic implosion takes place in seconds, during which the core reaches an inward velocity of up to 23% of the speed of light and temperatures up to $\sim 10^{11}$ K. 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 up to the escape velocity, forming a supernova explosion. Depending on the initial mass of the star, the remnants of the core give birth to a neutron star or a black hole.

Gravitational emission is expected only if an asymmetrical collapse of the core occurs. During the collapse phase, before the explosion, theoretical models predict strong gravitational associated with a strong neutrino emission from the neutronization experienced by the core. Many mechanisms during the gravitational collapse can ignite the burst of GWs. A non-comprehensive list of models for the emission mechanisms includes [3, 4]:

- Proto Neutron Star (PNS) pulsations;
- Rotational 3D instabilities;
- Rotating core collapse and core bounce;
- Post bounce convection and standing accretion shock instability (SASI).

The signal can last from few milliseconds to few seconds [5], and the energy converted into GWs before the explosion is of the order of $10^{-10} - 10^{-4} M_{\odot} c^2$. 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. As discussed in [2], this quantity is given by:

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

90% of the energy is conveyed in the neutrino channel. This model is consistent with observations from SN 1987A, where 19 neutrinos from core collapse have been measured [1].

CCSNe and ν s are emitted with a time delay ranging from 1 s and 20 s [5] in the inner regions of the star, the core of the proto neutron star (PNS), which cannot be studied electromagnetically, while 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 signals.

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.

3. Search proposal and strategy

We look for coincident events from GW and Supernova ν experiments in order to shed light on the physics of the core collapse. The search pipeline will be tested on archival ν and GW data before being applied to incoming data from the next generation detectors. The project currently involves several ν experiments, but the approach is general and can be extended to include more observatories.

Fig.1 shows the analysis pipeline setup based on two main stages: the background characterization and the study of the efficiency of detection 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 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.

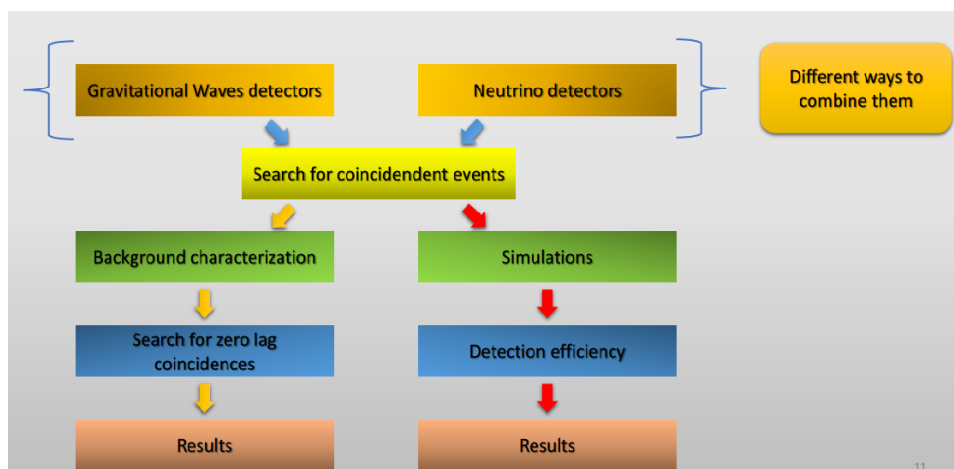


Figure 1 Scheme of the analysis pipeline setup.

One of the key aspects is to account for the single detector duty cycle and hence calculate the common observation time of the network of involved detectors or of the resulting subnetworks. The duty cycle is the percentage of time in which one detector (or a network of detectors) is active. The inactivity periods may be due to several factors, like ordinary maintenance, or any technical/scientific reason.

We need to set a global False Alarm Rate (FAR_{joint}) when searching for coincidences. This value represents a threshold that marks significant events for further investigation. For a Poisson process, this global rate is defined as:

$$FAR_{joint} = (FAR_1 \times FAR_2 \times \dots \times FAR_N) \times (2t_{coin})^{N-1}, \quad (2)$$

where FAR_i is the selected false alarm rate of the i -th detector and t_{coin} is the time coincidence window considered. The factor 2 accounts for the fact that coincidence searches are generally imposing the relative timing of a GW and neutrino event to be within t_{coin} , but not in a specific order.

The signals that we expect from this kind of sources are burst-like. Due to the fact that this kind of signals are un-modelled and buried inside the detectors background, we need to characterize the statistical distribution of the background in order to estimate the significance of the search and of a candidate GW-neutrino event. To estimate this distribution, we apply unphysical delays between the detectors data streams of the network, in order to remove true astrophysical signals and we search for temporal coincidences. 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 GWs emission. This delay may range between 1s and 20 s. Coincident triggers are selected in the shifted datasets and their distribution 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 (e.g. neutrino energy).

After the background characterization, we look for coincident events in the un-shifted datasets looking for any common signal exceeding the fixed threshold. In the case no results are found, we can set an upper limit on the rate of events assuming a given confidence level [6].

We also have to investigate how well our searching algorithm is able to find a true signal inside the stream of data. We will simulate different GW waveforms and neutrino fluxes from different models and inject them in the GW detectors and in the ν detectors datasets respectively. The detection efficiency will be determined by the percentage of the injected signal found in the output.

4. Involved experiments

In the context of this project, we are working with data from the three gravitational waves detectors of Advanced LIGO (aLIGO) [7] and Advanced Virgo (AdV) [8], and the three neutrino detectors Large Volume Detector (LVD) [9], Borexino [10] and IceCube [11]. A general overview of detectors is provided in the following.

Two main methods for detecting gravitational waves have been implemented in the currently working instruments. One method is to measure changes induced by gravitational waves on the distance between freely moving test masses. The other method is to measure the deformation of large masses at their resonance frequencies. The first idea is realized in laser interferometric detectors, whereas the second idea is implemented in resonant mass detectors.

Both aLIGO and AdV belong to the first group. AdV is currently in upgrading phase, while the aLIGO detectors were recently upgraded and have been taking data since mid-September 2015.

aLIGO is composed of two 4 km long interferometers arms located in a common vacuum tube in Hanford (USA) and in Livingston (USA). The Virgo detector is a 3 km long interferometer (operated by an Italian-French collaboration) located in Cascina (Italy). These detectors are designed to be power-recycled Michelson interferometers. In their first generation design, these detectors are sensitive to h values of the amplitude of $\sim 10^{-22}$. After the upgrade, the sensitivity will improve by one order of magnitude over whole the detection bandwidth. These instruments are expected to start a new GW astronomy era, measuring at least few sources per day.

Several neutrino detectors are sensitive to emissions from galactic CCSN [12].

LVD is a scintillator detector, operated by the Italian Institute of Nuclear Physics (INFN), able to 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. Its important feature is the possibility to detect neutrinos in several channels, allowing a more careful study of the energy characteristics of neutrino burst from collapsing stars [13, 14].

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 supernova within our galaxy. For this reason, Borexino is a member of the Supernova Early Warning System (SNEWS) [15].

The IceCube Neutrino Observatory is a neutrino telescope composed of thousands of sensors distributed over a cubic kilometer of volume under the Antarctic ice. It is designed to search 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. IceCube is also a member of SNEWS.

5. Benefits of the joint analysis

Searching coincidences of GWs and ν s will lead to a deeper understanding of the physics inside star cores. A distant event with low statistical significance in GW could have a neutrinos signature, which would increase the detection confidence in the joint analysis. 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 is to fix the joint false alarm rate (FAR_{joint}) of the search so that the single searches thresholds can be modified while keeping FAR_{joint} constant. We require a FAR_{joint} of the order of 1/1000 years. In this context, following Equation 2, we can tune our search modifying the thresholds on the single experiments. For example, in order to have the required FAR_{joint} , we can relax the ν threshold to the level of 1 event per day and obtain a GW threshold of the order of 1 event per 3 months. This allow us to include more events in the analysis from both the experiments, that otherwise we would have rejected because they have a low FAR . Including more event means improving the sensitivity of the experiment for a certain distance. The improvement for GW and ν searches that we would get are reported in Figure 2. Lowering the ν threshold would correspondingly lead to an increase of the probability to detect neutrinos from distant supernovae and also lead to a 10-20% gain in GW sensitivity (blue solid line with respect to the red dashed line), following [16]:

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

In Equation 3, 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 detector.

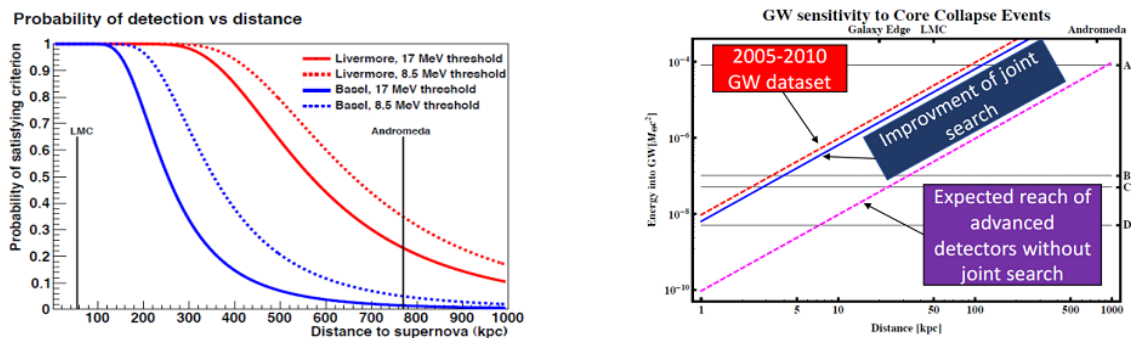


Figure 2 Estimated benefits of the joint search. The left panel shows the gain in probability of detecting two-neutrino events from distant CCSNe as function of the distance, for two different models. The right panel shows the sensitivity to CCSNe by GW detectors as limited by the efficiency of past and foreseen searches. The lines correspond to fixed search sensitivity at the GW detectors, for

narrow band signals at 554 Hz. The horizontal lines represent upper bounds on the energy release for four CCSNe models [3].

Previously studies relevant in the field of GW- ν supernova search are [17, 18].

6. Conclusions

The purpose of this paper is to expose the methodologies in the framework of the search for coincident gravitational wave and neutrino signals from Supernovae. This project is still at an early stage and the main effort focused on creating a common ground where two different communities could interface. For the moment we are re-analyzing archival data in order to set-up the methodologies and preparing the pipeline for new data from advanced interferometers. The future steps will address more in depth the design of the search and its tuning. Furthermore, it is important to characterize the detection efficiency of the network to incoming gravitational waves and neutrinos, by means of simulated signals injected into the data.

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References

- [1] Hirata K et al. 1987 Phys. Rev. Lett. **58** 1490
- [2] Castellani V 1985 Fondamenti di Astrofisica Stellare, Zanichelli Editore
- [3] C. D. Ott 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. Quantum Grav. **26** 245007
- [7] Abbott B and LIGO Scientific Collaboration 2009 Rept. Prog. Phys **72** 076901
- [8] Accadia T et al. 2012 JINST **7** P03012
- [9] Cadonati L, Calaprice F P and Chen M C 2002 Astropart. Phys. **16** 361
- [10] Agafonova N Y et al. 2008 Astropart. Phys. **28** 516
- [11] Halzen F, Jacobsen J E and Zas E 1996 Phys. Rev. D **53** 7359
- [12] Scholberg K 2012 Ann. Rev. Nuc. Part. Science **62** 81-103
- [13] Giusti P 2014 Pontifical Academy of Sciences Scripta Varia **119** Vatican City
- [14] Fulgione W 2006 Mem. S. A. It. Suppl. **9** 388
- [15] <http://snews.bnl.gov/>.
- [16] Abbott B and LIGO Scientific Collaboration 2008 Class. Quantum Grav. **25** 039801
- [17] Arnaud N et al. 2002 Phys. Rev. D **65** 033010
- [18] Arnaud N et al. 2004 Astropart. Phys. **21** 201-221