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Title : Understanding the core collapse supernova explosion mechanism

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Abstract :

Despite the marvelous progress of the theory, the explosion mechanism is still an open question and being able to measure the dynamics of matter at the onset of the phenomena would bring invaluable information to the gravitational core collapse physics field. The gravitational wave emission that is expected from a collapse bears the imprint of many of the phenomena that are at play. The main challenge of observing the gravitational wave emission is its very likely weakness that will limit the number of observable sources in the next decade with Advanced LIGO, Advanced Virgo et KAGRA. As the expected gravitational wave spectrum covers a very large and high frequency range (from few Hz up to several kHz), future projects like Eintein Telescope in Europe will be mandatory for this research. Yet, there are other limitations that require more developments.

White paper :

What is fairly known since the 1970's is the role of the neutrinos in the explosion mechanism (and this has been spectacularly observed in SN1987A). During collapse, the stellar core becomes opaque to neutrinos, producing a degenerate sea of trapped neutrinos within it, which subsequently diffuses out of the core on a timescale of order tens of seconds as the nascent proto-neutron star (PNS) cools down and deleptonizes.
The three-flavor neutrino flux emanating from the PNS could power itself a core collapse supernova (CCSN) via neutrino heating on delayed timescales of order one second. This phenomenon is central to most models today, with the exception of models of rare events involving significant rotation, which may be powered magneto-hydrodynamically and initiated on shorter timescales.

GWs are generated in CCSNe by time-dependent rotational flattening, particularly during collapse and bounce, and by prompt post-shock convection, PNS pulsations, non-radial turbulent flow in the neutrino-heated bubble, the activity of the standing accretion shock instability, asymmetric emission of neutrinos and explosive mass motions, and asymmetries associated with the effects of strong magnetic fields. Relevant for the GW signature is the equation of state, the mass of the progenitor, the rate of neutronization and cooling of the core (determined in part by the neutrino opacities), the neutrinos' conversion and the stellar core's initial angular momentum and mass density distributions. This broad description of the phases between bounce and explosion is now well supported by the current multidimensional numerical simulations in which all find similar features [Kotake 2013]. A general consensus from all simulations is that the expected GW signal is weak (GW released energy of the order of 10^{-9} $M_{\circ}$ c^{2}) and limits the discovery horizon of the current second-generation detectors to our galaxy. The expected galactic rate of type II/Ib supernova is also rather small (~1 per 30 years).

The neutrino emission which will be in coincidence with the GW emission, within about a second, should be detected by the current and future low energy neutrinos (LEN) detectors (Super-K/Hyper-K, DUNE, JUNO, KM3Net, IceCube, the LVD, Borexino and KamLAND) with a higher signal to noise ratio than the GW signal and a very precise time resolution (few milliseconds) which is a fundamental information to search for a low signal to noise ratio GW signal in GW data. The false alarm rate of GW searches can be significantly improved with temporal localization given by the neutrino signal, but above all, a reduced on-source window will allow to look for a signal buried in the noise. It is especially expected that the Supernova Early Warning System (SNEWS) [SNEWS] gathering many of the low energy neutrino experiments mentioned above will generate public alerts of well identified events by combining several neutrino detectors measurements (time of the neutrino burst, light curve, source localization, etc). Furthermore, there exists a strong correlation between the GW and neutrino signals as they are produced at the same interior location and will be powered by the downward accretion plumes associated with hydrodynamic instabilities present in the post-shock flow. These plumes and instabilities will modulate both signals [Takiwaki et al, 2018]. Developing joint analysis that associate GWs and LEN signals should bring new insights to the question.

The very likely diversity of the GW emission mechanisms that are at play makes the detection of a core collapse supernova GW signal very challenging. Furthermore, if the signal is likely to remain short (of the order of 1 s), it is expected to be wide band (from few Hz up to several kHz), with very different mechanisms in each frequency band. It is thus important to have detectors with sensitivity that remains optimal in a very large frequency band. The current ground based gravitational wave detectors offer the best opportunity for the next decade but their sensitivity must be increased and we are expecting a strong support from our institutions to Advanced Virgo + upgrade program to reach the initial advanced Virgo design sensitivity. It is worth to remind that at design sensitivity, very likely only a galactic core collapse supernovae would be detectable by the advanced detectors [Gossan et al. 2016].

Proposed third generation ground based gravitational wave detectors, such as the Einstein Telescope in Europe [Punturo et al.] will have a detection sensitivity approximately 10 times better than Advanced LIGO and Advanced Virgo and a very large frequency band response. The Einstein Telescope current proposed configuration consists of 3 pairs of km-scale interferometers positioned such that they form a triangular shape. Each interferometer pair represents one wide-band detector, in which one interferometer is optimized for gravitational waves at low frequencies (i.e., < 100 Hz) and the other for high frequencies (i.e., > 100 Hz). This unique feature would allow to cover the expected low frequency emission (<20 Hz) as well as the promising high frequency GW emission that can reach several kHz. The sensitivity improvement in both frequency bands would allow to better reconstruct the signal of a Galactic core collapse supernova and would also allow to increase the potential number of source by testing a volume of the universe 10 - 100 times further than our Galaxy limits [GWIC science Case]. Yet, in the next decade, the second generation of ground-based detectors will have to maximize their lifetime and sky coverage in order to not miss the next Galactic CCSN.

CCSN gravitational wave searches do not make use of the signal waveform. However, they take into account their main expected features: presence of a large amplitude burst emission of the bounce in case of highly rotating progenitor, stochastic GW emission in the post-bounce phase with a low frequency component that can be associated to the standing accreting shock instability phenomena and sharp but frequency increasing GW emission corresponding to different oscillation modes of the proto-neutron star. This is where having reliable and the most accurate waveforms is important. These waveforms are produced by very complicated numerical simulation codes that must include several features to produce realistic waveforms : precise neutrino transport, multi-dimensional and full general relativity simulation, MHD, … Few French groups have a large expertise in these simulations that require large computing power. As the community is rather small, collaborations with world-wide groups is mandatory and already exists (ERC MagBURST with Valencia and MPA-Garching groups, ERC Synergy proposal 2020-26 with Thomas Janka at MPA-Garching and Miguel Aloy in Valencia, collaboration with Kei Kotake at Fukuoka,...).
The impact of the French groups working on improved models of the nuclear interactions in extreme dense matter and on neutrinos' conversion in neutron stars would be invaluable to the construction of almost complete numerical simulation codes that could also generate gravitational wave waveforms. In that respect, we would like to underline that the two other proposals – "Probing extreme matter physics with gravitational waves" and "Neutrinos Astrophysics" – complement this one to form a coherent multi-disciplinary study.

These 3D simulations are fundamental to develop algorithms that aim at extracting the main parameters of the source [Torres-Forné et al. 2019] and identify which combination of mechanisms have been responsible for the explosion. The simulations also help at developing phenomenological models that could be useful for data analysis as proposed in by Cerda-Duran et al. This represents a real challenge for the next decade for both numerical relativity and data analysis communities.

References

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