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Gravitational Waves from core-collapse Supernovae

Alessandro Lella[a,*]

[a]Dipartimento Interateneo di Fisica "Michelangelo Merlin," Via Amendola 173, 70126 Bari, Italy
[a]Istituto Nazionale di Fisica Nucleare - Sezione di Bari, Via Orabona 4, 70126 Bari, Italy

E-mail: alessandro.lella@ba.infn.it

Galactic core-collapse Supernovae could be powerful sources of Gravitational Waves (GWs) induced by hydrodynamical instabilities and highly-time dependent anisotropic emission of neutrinos. In this work, we analyze the expected gravitational wave signals from two reference SN models started from 3D progenitors and evolved continuously in 3D up to late times after the core bounce ($t_{\rm pb} > 1.5$ s) by employing the `PROMETHEUS-VERTEX` neutrino transport code. For each considered SN model we point out how different features recognizable in GW signatures can be related to peculiar physical phenomena characterizing SN events, such as post shock-shock convection, standing accretion shock instabilities and anisotropic shock expansion. Finally, we discuss prospects of detection for current and future GW interferometers, highlighting that GW signatures from the next Galactic Supernova event can be reasonably considered in the reach of next-generation experiments working in the frequency range $f \sim 1 - 2000\,$Hz.

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[*] Speaker

1. Gravitational wave sources in core-collapse Supernovae

The comprehension of the physical mechanisms leading to core-collapse Supernovae (SNe) has been significantly deepened during the past five decades. Therefore, Supernova theory can be considered a field mature enough to be studied at the interface of gravitational, particle, nuclear and numerical physics. In particular, recent realistic 3D SN simulations have revealed that successful explosions can be self-consistently triggered only by accounting for anisotrpic emission of neutrinos from the protoneutron star (PNS) and large neutrino-driven convective instabilities [1–3], pointing out that non-spherical mass/energy flows have to be considered fundamental ingredients to allow these powerful events to happen. As pointed in Refs. [4, 5], these effects can induce a non-null quadrupole mass-momentum tensor, sourcing Gravitational Waves (GWs) in the frequency range $f \sim 1 - 2000\,\mathrm{Hz}$.

In this work, we employ hydrodynamical outputs and neutrino data from two different 3D SN models by `GARCHING` group, originated from progenitors simulated in 3D as well. The s18.88 model is described in Ref. [6] and considers a non-rotating, solar-metallicity 18.88 $M_\odot$ 3D progenitor leading to a neutron star baryonic mass $M_{\rm NS} = 1.65\,M_\odot$. The second model considered, here labeled as s12.28, is launched from a 3D 12.28 $M_\odot$ progenitor and it is evolved till ~ 4.8 s after the core bounce. Both models lead to a successful explosion when employing a full three-dimensional evolution. In this regard, we stress that both simulations are initiated, collapsed and then evolved during the explosion phase completely in 3D by employing the `PROMETHEUS-VERTEX` [7] neutrino transport code.

1.1 Gravitational wavae from hydrodynamical instabilities

Anisotropic mass flows due to prompt post-shock overturning convection, neutrino-driven turbulence, turbulent accretion through the shock and onto the PNS and aspherical explosive mass flows may induce a significant emission of gravitational waves. Following the treatment outlined in Ref. [8], we have estimated the GW signals expected from our reference SN models. The upper panels of Fig. 1 display GW signals due to matter motion for both polarization states and for both models considered in the analysis, assuming an observer located in the equatorial plane. We can appreciate that the s12.28 model shows non-negligible GW amplitudes oscillating around zero during the first tens of milliseconds after the core bounce. As described in Refs. [9–11], this feature can be associated to prompt post-shock convection. On the other hand, the s18.88 model does not show any hint for prompt convection. After this prompt post-shock emission, both models show a quiescent phase at $t_{\rm pb} \sim 50 - 200\,\mathrm{ms}$ during which neutrino-driven instabilities in the hot-bubble build up. Then, around the shock revival ($t_{\rm pb} \sim 200\,\mathrm{ms}$), convection in the hot bubble and the strengthening of standing accretion shock instabilities (SASI) give rise to a strong stochastic signal which peaks around $t_{\rm pb} \sim 0.5$ s. In particular, the signal is powered by the accretion of the infalling plumes during the explosion [11, 12] which strike the PNS surface strengthening its modal oscillations. In the time window $t \sim 0.7 - 1$ s the effects due to accretion plumes attenuate, and the signal evolves with low amplitudes. Finally, at $t_{\rm pb} \gtrsim 1$ s exploding models display a slow and quasi-monotonic rise of the signal due to asymmetric shock expansion, followed by a long-term "memory" behavior characterized by a large-offset constant strain when explosive mass flows develop [9, 11].

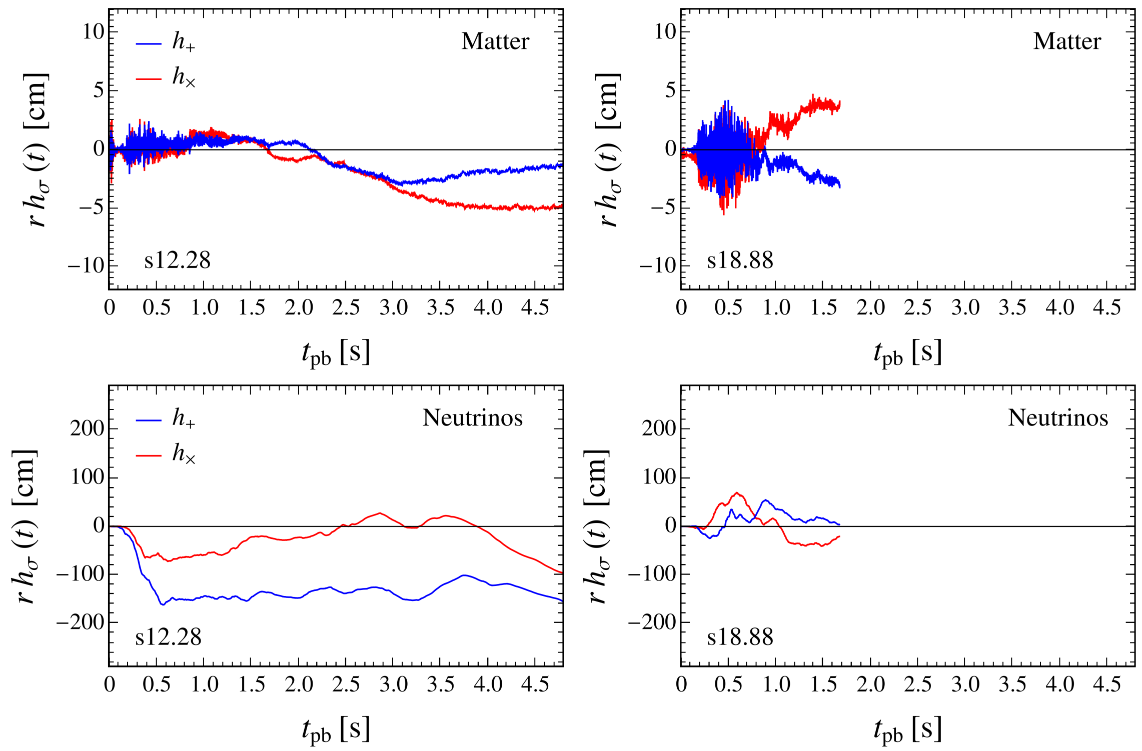

Figure 1: GW signals sourced by hydrodynamical instabilities (*upper panels*) and anisotropic neutrino emission (*lower panels*). *Right* and *left panels* refer to the s12.28 and s18.88 SN models, respectively. Blue and red curves display the expected signals for the two possible GW polarization states.

1.2 Gravitational waves from anisotropic neutrino emission

As pointed out in Refs. [4, 5], anisotropies in the emission of neutrinos during core-collapse SNe could source a slowly-oscillatory perturbation in the space-time characterized by a long-term secular evolution, commonly known as *neutrino memory effect* [13, 14]. GW signals induced by non-spherical neutrino emission are computed by following the formalism in Ref. [8]. The lower panels of Fig. 1 show neutrino GW emission considering both polarization states and both models included in our analysis. For illustration, we refer to an observer located in the equatorial plane of the simulation. We can observe that, just after the core bounce, signals assume values always compatible with zero, since the neutrino emission can be considered essentially isotropic. Then, at $t_{\rm pb} \sim 0.2$ ms, post-shock convection and SASI start to power highly time-dependent anisotropic neutrino emission. Therefore, signals start to increase in magnitude over time scales $O(100)$ ms, acquiring values $r\,h \sim O(100)$ cm. Finally, at late times, signals are characterized by a slowly-changing secular evolution which is peculiar for memory effects.

2. Detection prospects

In Fig. 2 we display the amplitude spectral densities defined as in Ref. [15] referring to the combined matter and neutrino signals for both models considered in our analysis. In this figure, we assume an observer placed at a typical Galactic distance from the location of the SN event

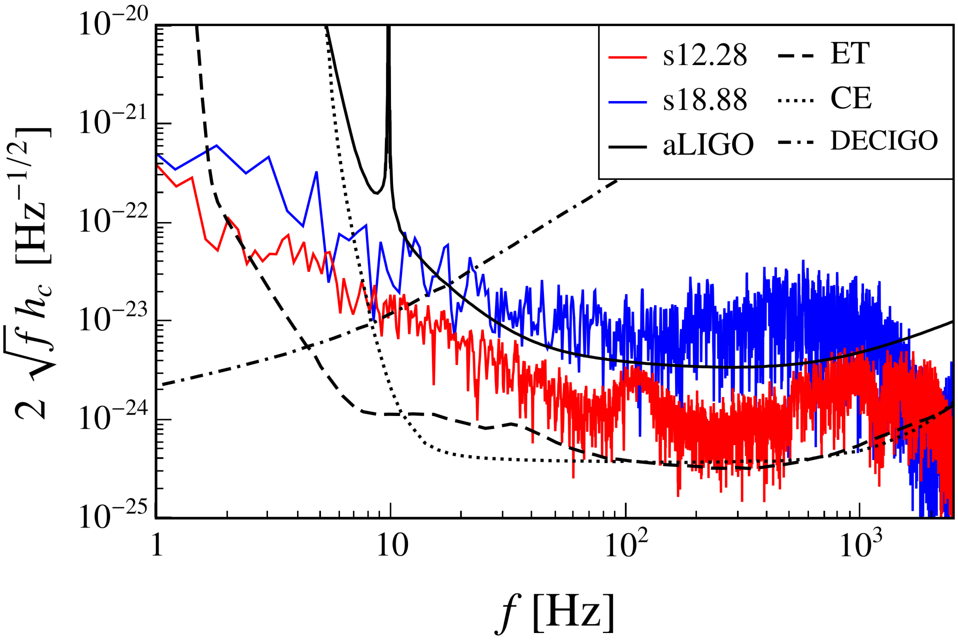

Figure 2: Combined neutrino and matter spectral energy densities for both SN models considered in this work. These spectra refer to the case of a SN event occurring at a typical Galactic distance $d = 10$ kpc. Black curves depict the sensitivity curves of current and programmed GW experiments operating in the frequency range of interest.

$d = 10$ kpc. The low frequency behavior $f \sim 1 - 10\,\text{Hz}$ is completely dominated by anisotropic neutrino emission, while the contribution from non-radial mass flows arises at higher frequencies $f \sim 10\,\text{Hz}$. Moreover, the s18.88 is characterized by larger values of the spectral density with respect to the s12.28 model. This is in agreement to the outcomes of previous works on the topic, which showed that higher progenitor mass models are typically characterized by higher characteristic strains. Together with GW spectra for our SN models, in Fig. 2 we also report the sensitivity curves for current and programmed GW detectors operating in the frequency range of interest, i.e. advanced LIGO (aLIGO) [16], Einstein Telescope (ET) [17, 18], Cosmic Explorer (CE) [19] and DECIGO [20]. We can appreciate that the high-frequency component of the expected signal from our s18.88 model is in the reach of aLIGO, while the matter GW spectrum for the s12.28 model is out of the sensitivity curve for this experiment. Nevertheless, the predicted GW signals for both our SN models are clearly in the reach of future GW detectors if assuming a SN event occurring a typical Galactic distance $r = 10$ kpc. In particular, CE is able to capture completely the high-frequency modes associated to hydrodynamical instabilities for both s12.28 and s18.88, while DECIGO could resolve the neutrino GW spectra in the low-frequency band. Interestingly, ET is able to detect a large part of the combined neutrino and matter GW spectra ranging within $3\text{Hz} \lesssim f \lesssim 2000\,\text{Hz}$.

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