2017 Kavli Astrophysics Summer School: report on research

John Ryan Westernacher-Schneider

October 1, 2017

During the program in Copenhagen, I collaborated with Philipp Moesta, Evan O'Connor, Erin O'Sullivan, Irene Tamborra, and Meng-Ru Wu. We conducted a study of core-collapse supernovae using the FLASH code for numerical simulations. Our focus was on cases where the core has a non-negligible rotation just prior to collapse. This choice allowed for a simplified control over the system behaviour, since the initial rotation rate is set as a parameter. Given our ability to detect astrophysical neutrinos from such an event, as well as the recent demonstration of our ability to detect gravitational waves, it was prescient that we leverage both signals to probe the supernova progenitor. Fig. (1) shows a representative set of gravitational wave strain and neutrino luminosity time series from one of our simulations, with the gravitational wave strain scaled to a source at 1 kpc distance.

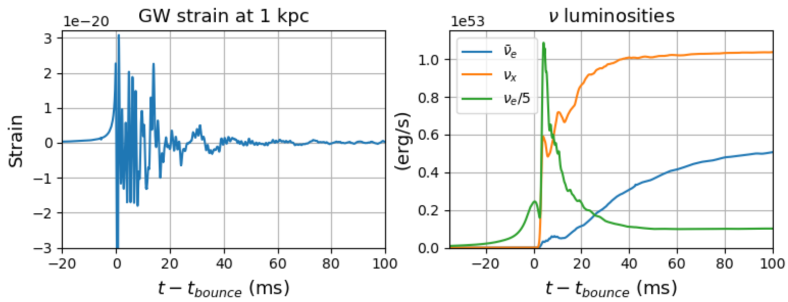

Figure 1: Representative gravitational wave strain (Left) and neutrino luminosity (Right) time series from our simulations. The gravitational wave strain is scaled to a source at 1 kpc distance. Note that ν_x denotes the combination of all non-electron flavours.

During the first ~100 ms after core bounce, we identified correlated power at several frequencies in time series of the gravitational wave strain and the neutrino luminosities. These correlations were robust against changes in grid resolution and neutrino simulation schemes, which supports this being a physical effect. Note that those neutrino flavours which have suppressed charged-current interactions in this system (μ- and τ-flavours) will probe deepest into the star – we correspondingly noticed that those flavours had the strongest imprint of correlated power with the gravitational wave strain (see Fig. (2)). During these early times, the oscillating core is expected to dominate the gravitational wave signal, since convection behind the radial shockwave has not yet reached peak amplitudes. This therefore suggests that the core oscillations are responsible for imprinting the observed frequencies onto the neutrino signals.

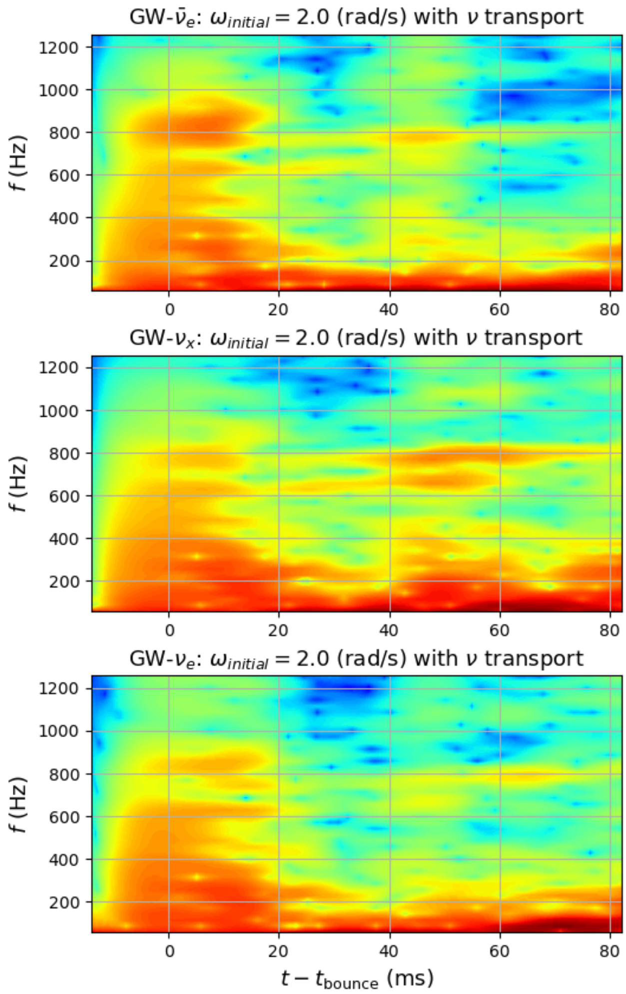

Figure 2: Cross-spectrograms between the gravitational wave strain (GW) and the neutrino luminosities for $\bar{\nu}_e$ (Top), ν_x (Middle), and ν_e (Bottom), where ν_x is comprised of all of the non-electron flavours. We show a representative case with the initial rotation rate $\omega_{\rm initial} = 2$ rad/s, and with an M1-closure neutrino scheme. Each plot is normalized by the total power in each signal, and the color scales are shared, which allows for a qualitative comparison between plots. The non-electron flavours ν_x are seen to have the strongest correlated power around $f \sim 800$ Hz and 700 Hz. This is what one would expect if those frequencies originated from regions in proximity to the oscillating core, since the ν_x suffer least from reprocessing within the rest of the star.

Since the core spins up to hundreds of Hz as it collapses, and its rotation is differential, the resulting proto-neutron star is well outside of the first-order perturbative regime for which r-mode oscillation frequencies are known. Thus, I intend to extract oscillation information directly from the simulations. By using the Python module 'yt', I can perform an analysis of the mass density on the grid. I will first identify the boundary of the core using a threshold condition on its velocity profile. Following this, a projection of the mass density of the core onto a mode basis will permit identification of which modes are responsible for the observed 700 Hz and 800 Hz signals. Such correlated gravitational wave and neutrino signals, therefore, could permit direct measurement of the oscillation modes of a proto-neutron star in this highly dynamical regime.

We also wish to determine the distance at which this correlated power can be seen with current or planned detectors. Part of this analysis involves converting our raw numerical strains/luminosities into simulated measured signals. Codes exist for this purpose, and my collaborators have access and experience using them. However, we must also determine a threshold for ruling out a false-positive. Since the gravitational wave strain has the strongest power at the aforementioned frequencies, the threshold will be determined by cross-correlating the gravitational wave strain from rotating cores and the neutrino signal from a non-rotating one. A cross-spectrogram will still have some shared power at those frequencies in this case, since the neutrino signals have some amount of power everywhere, but the rotating cases will have the strongest correlation. So this test can determine a baseline correlation strength, above which a false-positive can be ruled out.