BH Formation and Multi-messenger Signals from 3D Rotating CCSN Simulations

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3D Core-collapse Supernova

- Ref: 2010.02453
- Progenitor mass: 40 solar mass.
- 3 initial angular velocities: 0, 0.5, 1 rad/s.
- No BH formation are found in rapidly-rotating model.
- BH formation at 776 ms postbounce and 936 ms postbounce for non-rotating model and slowly-rotating model.
- Slowly-rotating model: extremely high GW frequency (f ~ 3000Hz) at BH formation.
- The parameter space of CCSN explosion models and multi-messenger signal predictions are not fully explored.
3D Core-collapse Supernova

- CCSNe with non-rotating intermediate-mass progenitors show weak GW emissions.
- Massive progenitors with fast rotation, might provide stronger GW emissions, detectable at extra-galactic distances by the current LIGO-Virgo-KAGRA network.
- The evolution of GW frequencies from core bounce to BH formation reflect the evolution and oscillation of the central proto-neutron star (PNS), which are crucial probes to understand the microphysics and supernova engine(s).
Figure 1. Time evolution of averaged shock radius, central density, mass accretion rate (measured at $r = 500$ km), neutrino luminosities, neutrino mean energies, and diagnostic explosion energy. Different colors represent simulations with different rotational speeds. The thin green line shows a 2D counterpart of the non-rotating model in Pan et al. (2018). A moving averaged filter with a window of 3 ms is applied to the neutrino luminosity and mean energy to reduce noise.
Figure 4. Time evolution of the direction of the rotational axes of the PNS in models with different initial rotational speeds. The origin of this polar plot is pointed to the direction of the negative z-axis in the simulation box. The distance to the origin represents the azimuthal angle ($\phi$) of the rotational axis, and the phase angle shows the polar angle ($\theta$) of the rotational axis. Colors from blue to yellow represent the simulation time after core bounce. Note that the azimuthal angle limits from left to right panels are 180°, 0.5°, and 2.0°.
Time Evolution of Standing Accretion Shock Instability

Figure 5. Time evolution of SASI amplitudes in different directions. Different colors represent different initial rotational speed. Amplitudes are normalized by the averaged shock radius ($a_{00}$).
Figure 7. Evolution of PNS angular velocity and rotational periods. Different colors represent different initial rotational speed.
GW Emission

Figure 8. Gravitational wave signals at around core bounce. Different colors represent different initial rotational speed.
Figure 9. Spectrograms of GW strains after core bounce, as observed from the equatorial direction. Different rows represent models with different initial rotational speed and different columns indicate signals with different polarization.
GW Emission

Figure 10. Similar to Figure 9, but as observed from the polar direction.
Figure 11. The characteristic GW amplitudes, $h_{\text{char}}$, for the three 3D models with different initial rotational speeds at 10 kpc. The solid (dashed) black line represents the designed sensitivity curve of the advanced-LIGO (KAGRA).
Detection using Machine Learning

- Injection of the CCSN GW into the background of O3 data.
- Detection: Gstlal, cWB.
- Classification of BH rotation, PNS angular velocity?