A Model for Gravitational Wave Emission from Neutrino-Driven Core-Collapse Supernovae

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Summary

Using a suite of progenitor models (12, 15, 20 and 40 $M_\odot$) and neutrino luminosities in two-dimensional (2D) simulations, we investigate the gravitational-wave (GW) emission from postbounce phases of core-collapse supernovae (CCSNe). We characterize the matter GW signatures of prompt convection, steady-state convection, the standing accretion shock instability (SASI) , and asymmetric explosions. The characteristic GW frequency evolves from ~100 Hz just after bounce to ~300-400 Hz, with higher frequencies corresponding to higher mass progenitors and models that take longer to explode by the neutrino mechanism. After vigorous convective/SASI motions start, the GW strain amplitude increases roughly tenfold and shows features that strongly correlate with downdrafts striking the protoneutron star (PNS) ``surface." During explosion, the high frequency signal wanes and is replaced by a strong low frequency, ~10s of Hz, signal that reveals the general morphology of the explosion (i.e. prolate, oblate, or spherical). However, ``seeing" the explosion morphology requires direct observations of the GW strain amplitude at low frequencies, and current and near-future GW detectors are sensitive to GW power at frequencies $\geq$50 Hz. In practice, the signature of explosion for these detectors will be the abrupt reduction of detectable GW emission.

For the stages before explosion, we propose a model for the source of GW emission that explains the characteristic frequencies and amplitudes. Downdrafts of the postshock-convection/SASI region strike the PNS ``surface" with large speeds and are decelerated by buoyancy forces. We find that the GW amplitude is set by the magnitude of deceleration and, by extension, the downdraft's speed. However, the characteristic frequencies are primarily independent of these speeds (and turnover timescales), but are set by the deceleration timescale, which is in turn set by the buoyancy frequency (Brunt-Väisälä frequency) at the lower boundary of postshock convection. Since the buoyancy frequency is determined by global and local properties, the GW characteristic frequencies are dependent upon a combination of the dense-matter equation of state (EOS) and the specifics that determine the gradients at the boundary, including the mass-accretion-rate history, the EOS at subnuclear densities, and neutrino transport. In summary, detection of GWs from CCSNe may reveal details of the core structure and dynamics of the explosion mechanism.

What determines the characteristic frequencies and amplitudes of gravitational waves?

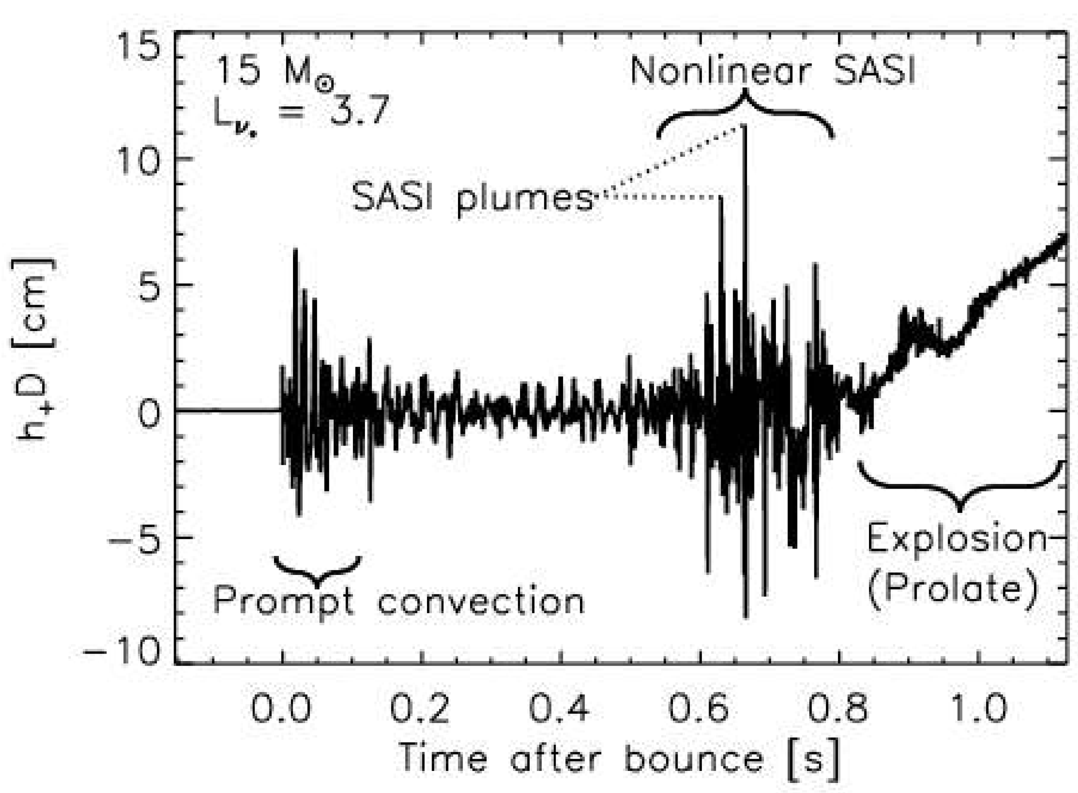
How do these change with progenitor mass and neutrino Luminosity?

What is the GW signature of explosion?

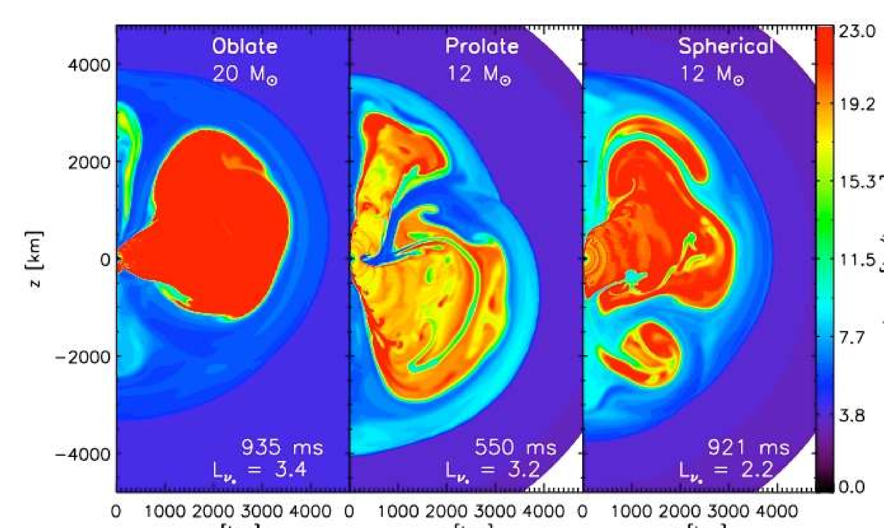
Parameter study to answer these questions

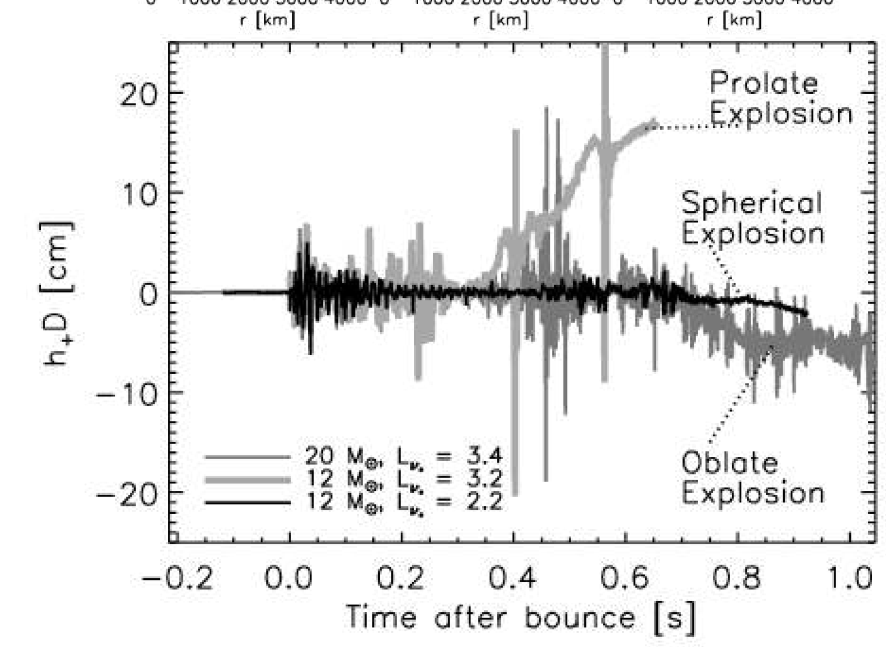
- 2D simulations using BETHE-hydro
- Neutrino Luminosity (Local heating and cooling)
- 12, 15, 20, and 40-$M_\odot$ progenitor models
- Shen EOS

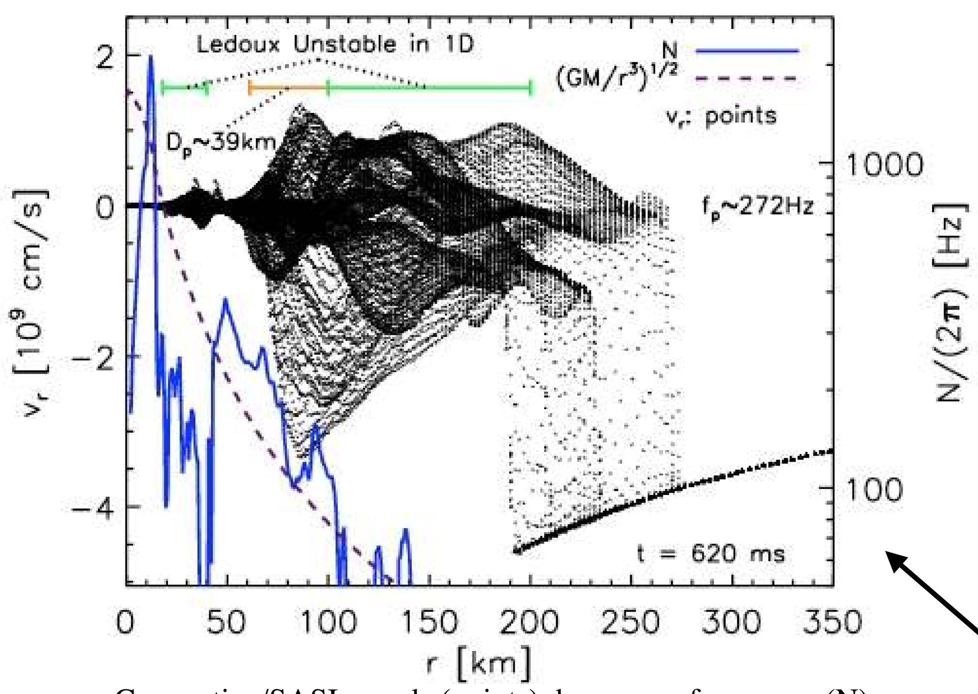
GW emission from post bounce phases



GW Signature of Asymmetric Explosions

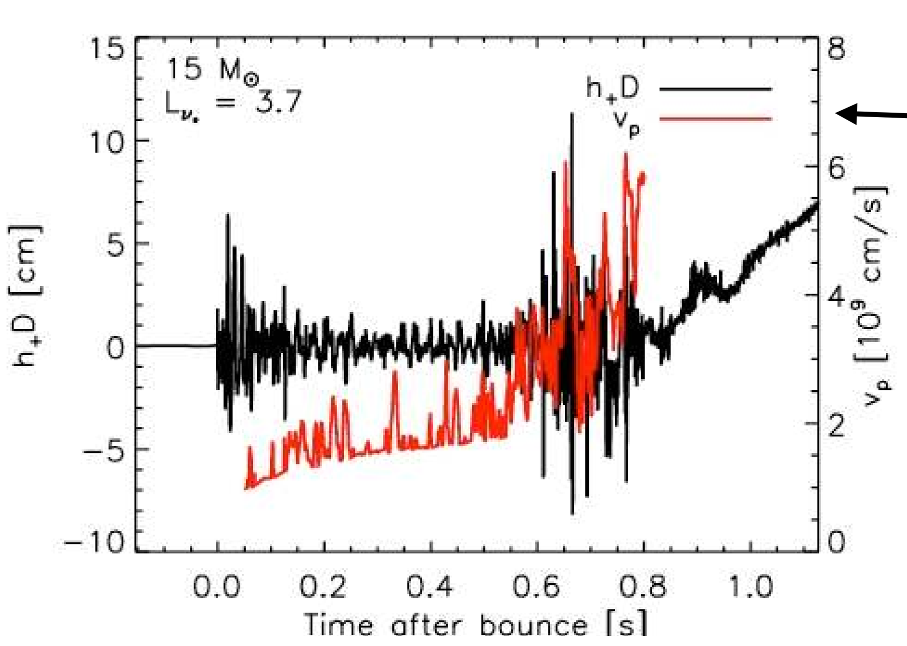


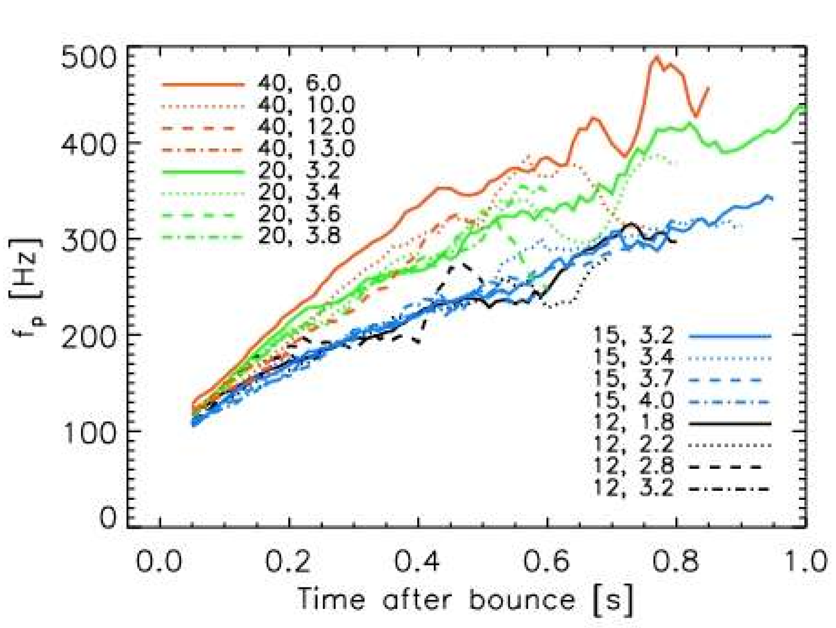




Gravitational Wave Emission Model

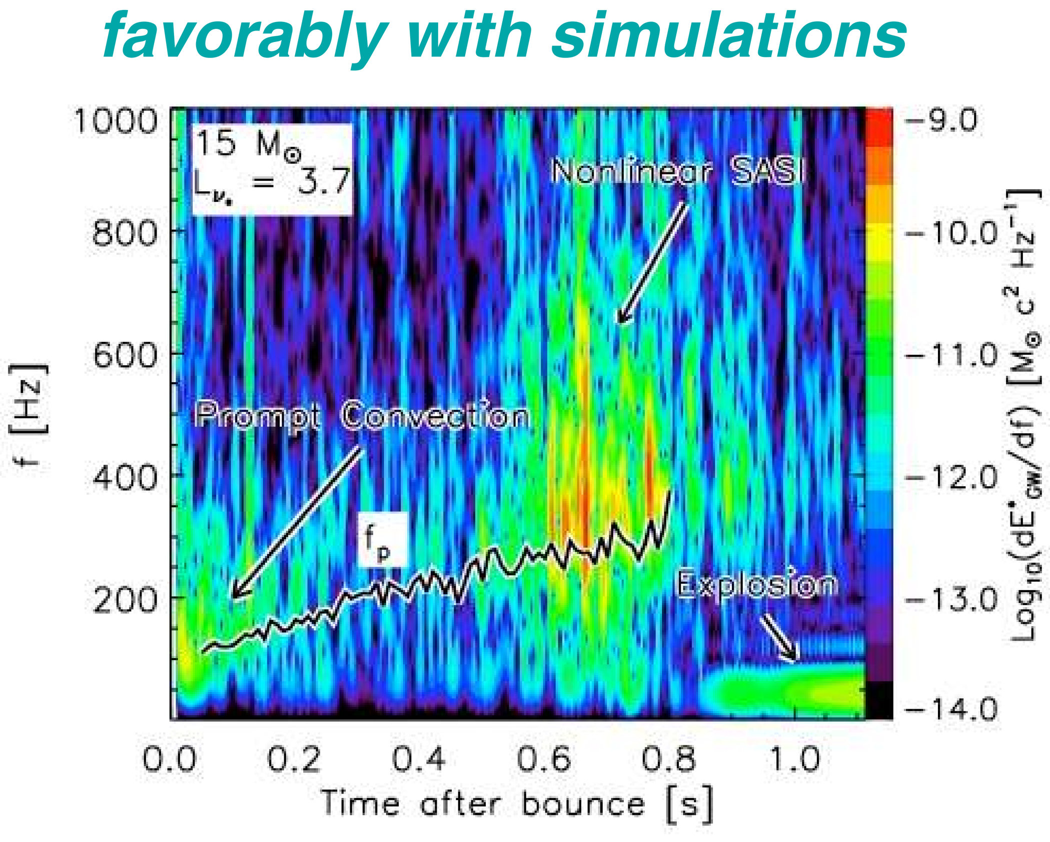
- Postshock convection/SASI plumes strike the protoneutron star "surface" with velocity (v_p)
- Buoyancy force at "surface" applies impulse
- Buoyancy impulse has characteristic frequency (f_p) and penetration depth (D_p)
- $f_p \propto N_{turn}$ (the buoyancy frequency at the turn-around depth) and is peak GW frequency
- GW amplitude $\propto f_p v_p$

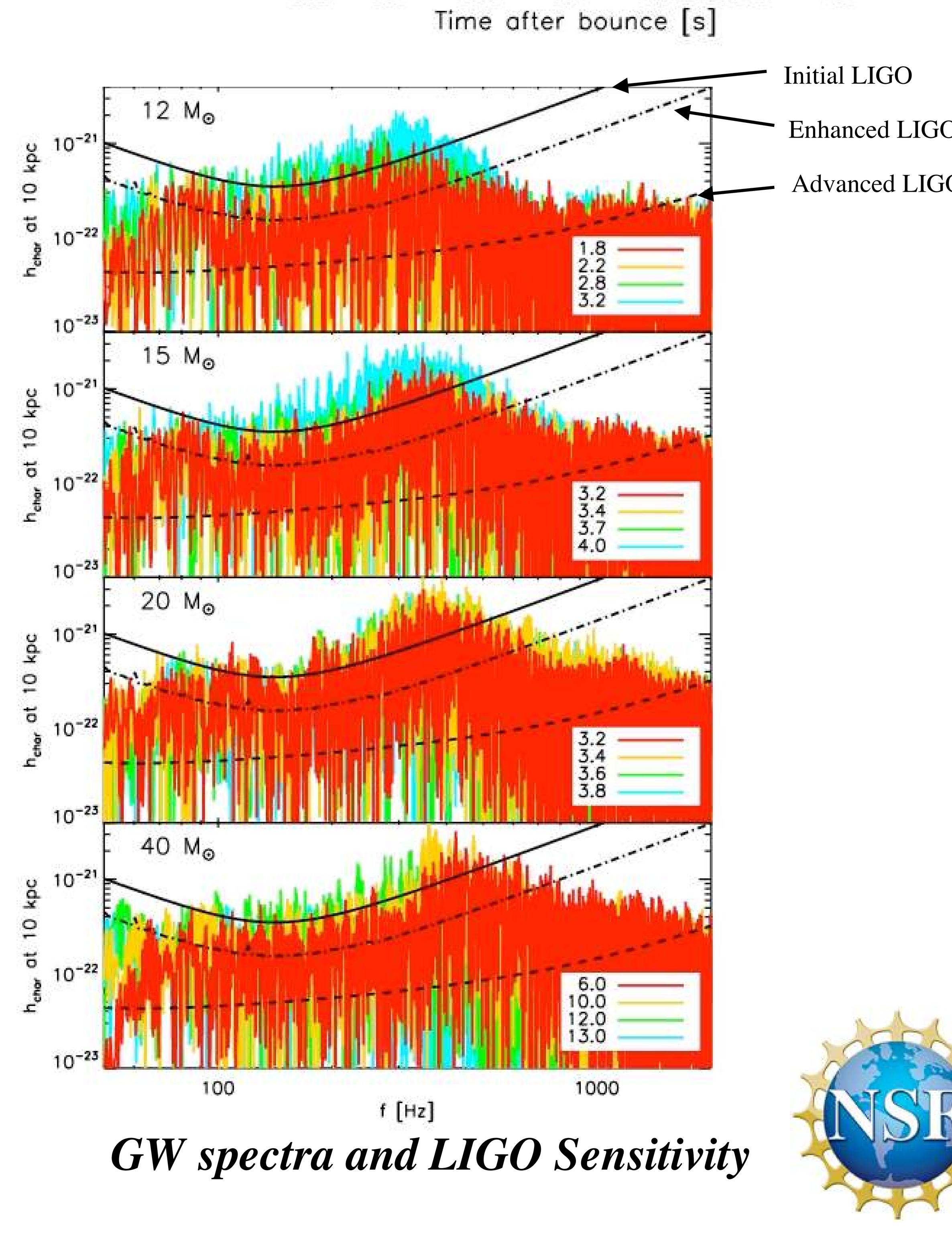




Characteristic frequency as a function of progenitor model, neutrino luminosity and time after bounce. **Higher mass progenitors and models that explode later (lower neutrino luminosities) show higher frequencies.**

GW emission model compares favorably with simulations





GW spectra and LIGO Sensitivity

For more information see arXiv:0907.4762 or contact Jeremiah W. Murphy at jmurphy@astro.washington.edu