Relativistic Explosion Models of Core-Collapse Supernovae

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Introduction

Supernova explosions, which mark the death of massive stars (>8$M_\odot$), are among the most spectacular events in the universe, and present one of the greatest challenges in computational astrophysics. After more than 40 years of modelling, the complex interplay of hydrodynamics, neutrino transport, general relativity (GR) and nuclear physics underlying the explosion mechanism is still not completely understood. Neutrino heating, hydrodynamical instabilities, magnetic fields and energy deposition by acoustic waves are considered as possible factors that can play a role in the explosion mechanism (see [1,2] for reviews).

Supernovae and General Relativity

Despite the fact that relativistic effects play an important role in the supernova core due to the compactness of the proto-neutron star ($GM/rc^2 \approx 0.1...0.2$) and the occurrence of high velocities, the influence of GR has so far only been studied either on the basis of 1D neutrino transport models [3] or (in the numerical relativity community) without state-of-the-art neutrino transport (see [4,5] for an overview). As 1D simulations have shown a huge impact of GR on critical factors like the neutrino luminosities and the shock position [3], some multi-D neutrino hydrodynamics simulations have relied on a pseudo-Newtonian "effective potential" approach to incorporate some GR effects [6,7,8], but the quality of this approximation in the context of multi-D models is yet to be determined.

With the first code combining multi-dimensional GR hydrodynamics and energy-dependent neutrino transport [9], we can now **test the (pseudo-)Newtonian approximation**, assess the **influence of GR on the heating conditions**, and determine observable signatures (in particular **gravitational waveforms**) from the supernova core more accurately.

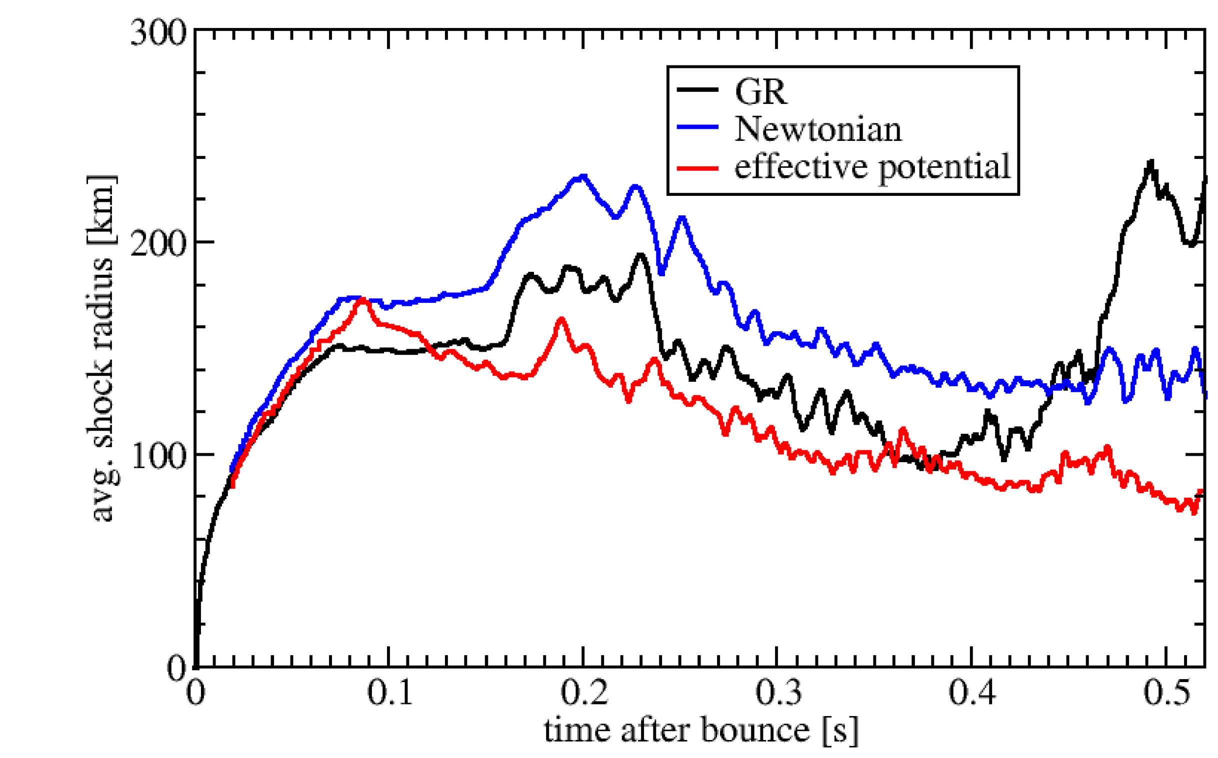

Fig. 2.: Shock position for the relativistic, pseudo-Newtonian, and purely Newtonian 15$M_\odot$ model. While the shock initially stagnates at the smallest radius in GR, the GR model soon overtakes the pseudo-Newtonian model. In the Newtonian case, relatively large shock radii are maintained, but nevertheless no explosion develops.

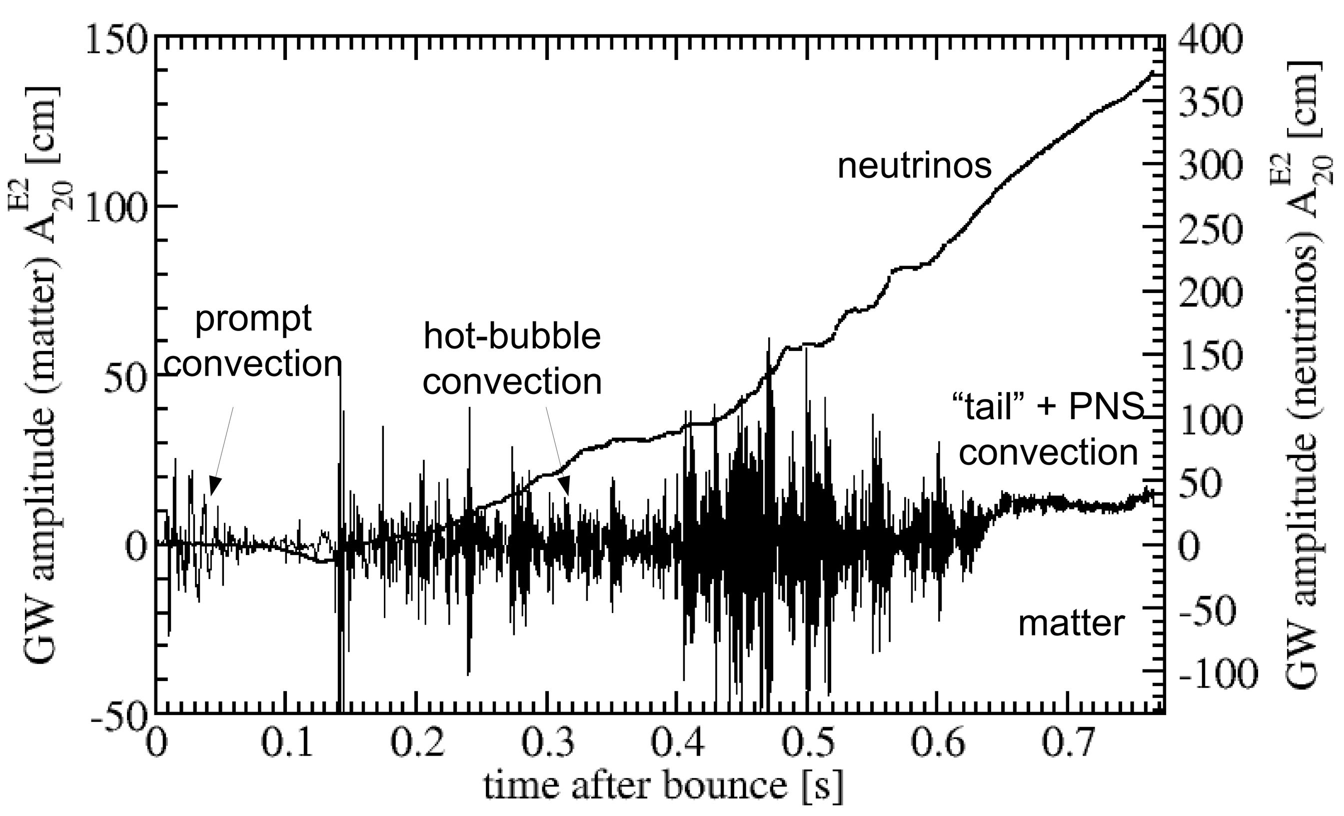

Fig. 5.: Matter and neutrino gravitational wave signal for relativistic 15$M_\odot$ model.

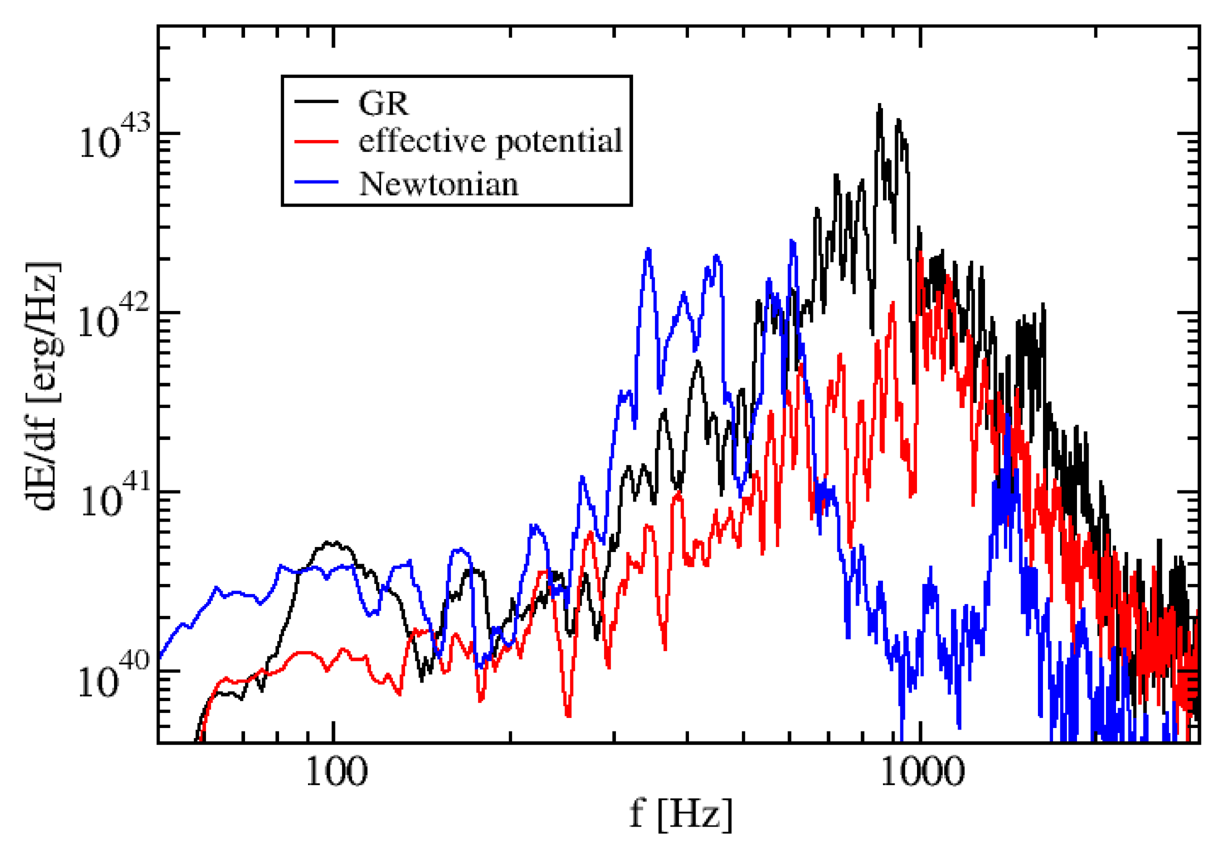

Fig. 6.: Gravitational wave energy spectra for the first 500ms after bounce for the different 15$M_\odot$ models (GR, effective potential, purely Newtonian).

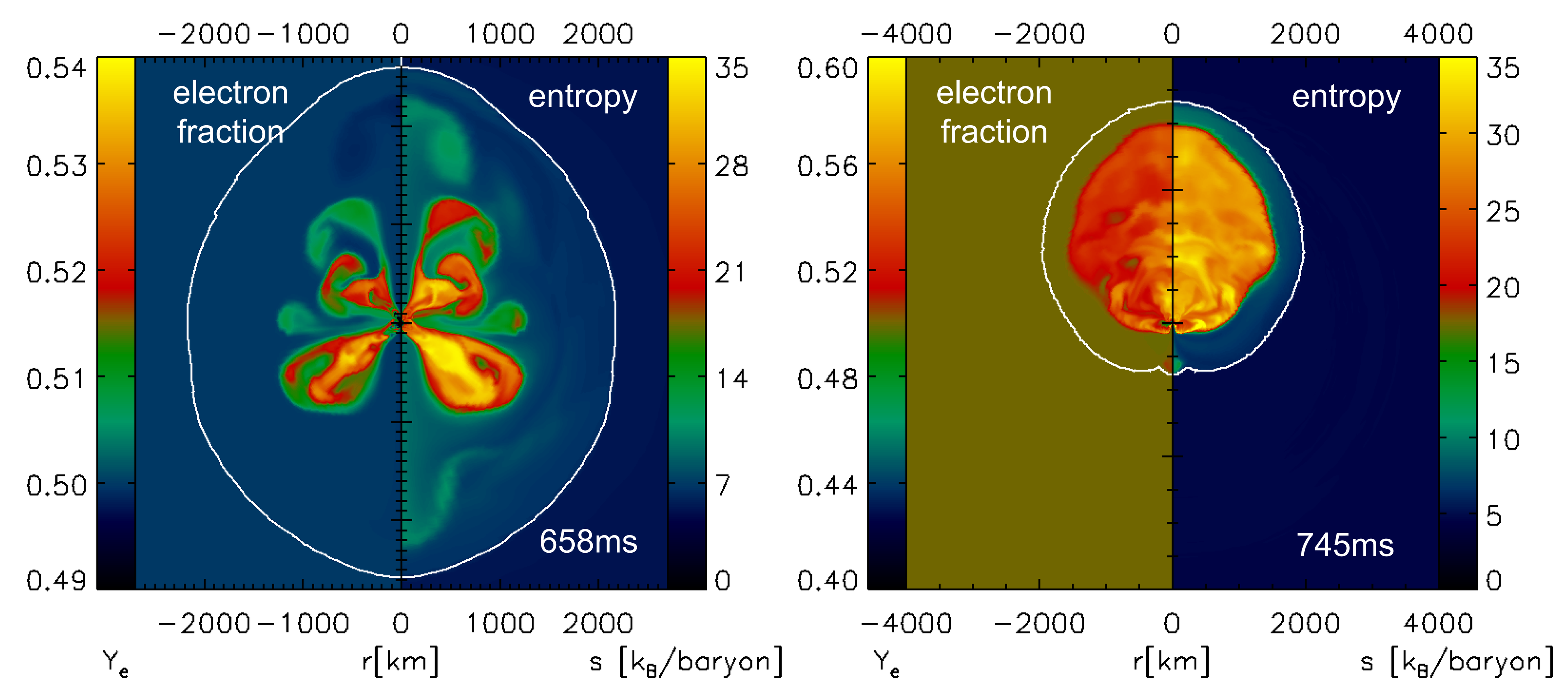

Fig. 1.: Explosion geometry for the relativistic 11.2$M_\odot$ and 15$M_\odot$ simulation, visualized at a time of 658ms and 745 after bounce, respectively. The left and right half of the panels show the electron fraction Y_e and the entropy s, and the position of the shock is indicated by a white curve.

Heating Conditions and Explosion Dynamics

We conducted relativistic 2D simulations of supernova explosions for an 11.2$M_\odot$ [10] and a 15$M_\odot$ [11] progenitor, which were supplemented by Newtonian models with and without a modified gravitational potential for the 15$M_\odot$ star. In the GR case, we obtain SASI-aided explosions for both progenitors, which are launched ~150ms and ~400ms after bounce, respectively. For the 15$M_\odot$ progenitor, neither the purely Newtonian model nor the effective potential model explodes (Fig. 2). Strong SASI activity plays a major role during the explosion of the 15$M_\odot$ model, which develops an extremely strong hemispherical asymmetry (Fig. 1), which allows to sustain high accretion rates and neutrino heating for several hundreds of ms after the onset of the explosion.

The different outcome of the 15$M_\odot$ model compared to its (pseudo-)Newtonian counterparts is a result of **more favourable heating conditions in the GR case**, where the critical ratio τ_{adv}/τ_{heat} between the advection and heating time-scale is larger by a factor of ~2 (Fig. 3). Higher electron and electron antineutrino luminosities and mean energies (Fig. 4) from a hotter proto-neutron star surface are ultimately responsible for the more optimistic evolution; they result in significantly higher heating rates per baryon, and the effect of increased heating is further magnified by more violent SASI activity. With full GR hydro, this overcompensates the competing effect of stronger shock retraction compared to the purely Newtonian case, which cancels the gain from stronger heating in our effective potential model.

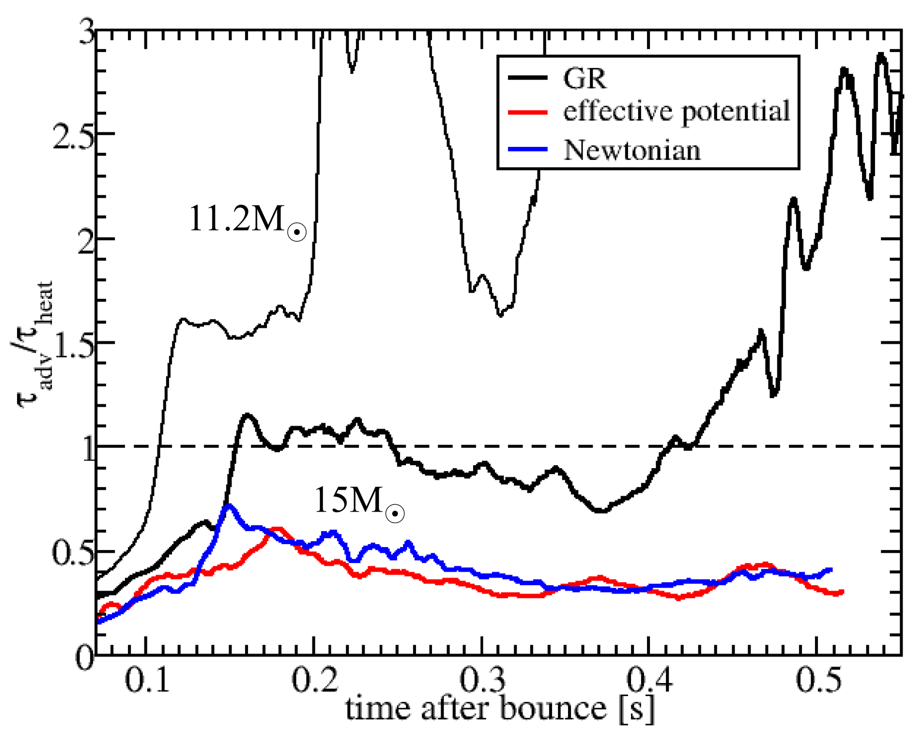

Fig. 3.: The ratio τ_{heat}/τ_{adv} between the heating and advection time-scale for the 11.2$M_\odot$ and 15$M_\odot$ models. Values of ~1 indicate the development of a runaway situation that will end up in an explosion if the favourable heating conditions are maintained for a sufficiently long time.

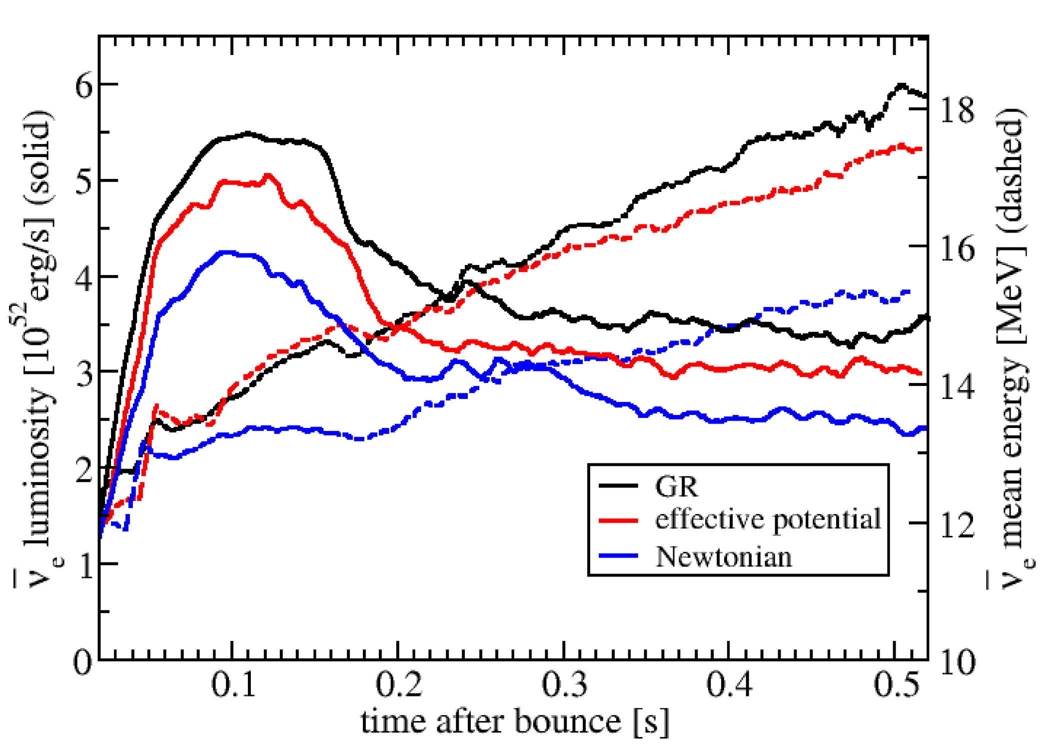

Fig. 4.: Electron antineutrino luminosities and mean energies at the gain radius for the 15$M_\odot$ models; note the clear hierarchy between the different cases (GR, effective potential, purely Newtonian)

Gravitational Wave Signal

Gravitational wave signals computed for our explosion models exhibit all the features known from Newtonan studies [12,13,14]: A low-frequency signal from prompt convection and early SASI activity is followed by a stochastic high-frequency signal from hot-bubble convection, and finally by a weak signal from proto-neutron star convection which is superimposed on a tail resulting from asymmetric shock expansion (Fig. 5). In addition, anisotropic neutrino emission also contributes significantly in the low frequency range.

Despite qualitative similarities, GR effects strongly affect the gravitational wave spectrum (Fig. 6). GR shifts he typical frequencies for the signal from prompt and hot-bubble convection upward by 25%...50% compared to the purely Newtonian case. The agreement with GR is much better for the effective potential model (typically within ~20%) although sizeable differences remain (as a result of a different density stratification outside the neutrinosphere). GR effects on the frequency spectrum are thus more than comparable to the variations seen for different nuclear equations of state [12].

References

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