General relativistic hydrodynamics of non-convex stellar collapse: gravitational waves

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Introduction

An open issue in relativistic astrophysics is the knowledge of the equation of state (EOS) describing the thermodynamical properties of high-density matter. Such extreme conditions are achieved in the cores of neutron stars.

With the recent detection of gravitational radiation, a significant new channel to collect complementary information and improve our understanding of the dense-matter EOS will soon be opened.

Its properties and the possible existence of exotic states may critically influence the stability and dynamics of these objects. The dense-matter EOS also plays a fundamental role in the evolution (on a hydrodynamical timescale) of scenarios of relativistic astrophysics such as core-collapse supernovae, short and long-duration progenitors of gamma-ray bursts, the cooling of protoneutron stars, the formation of stellar-mass black holes, or the merger of compact-binary systems.

Form a theoretical point of view, the existence of such exotic states of matter in the dense-matter EOS also requires the analysis of the “convexity” of the EOS.

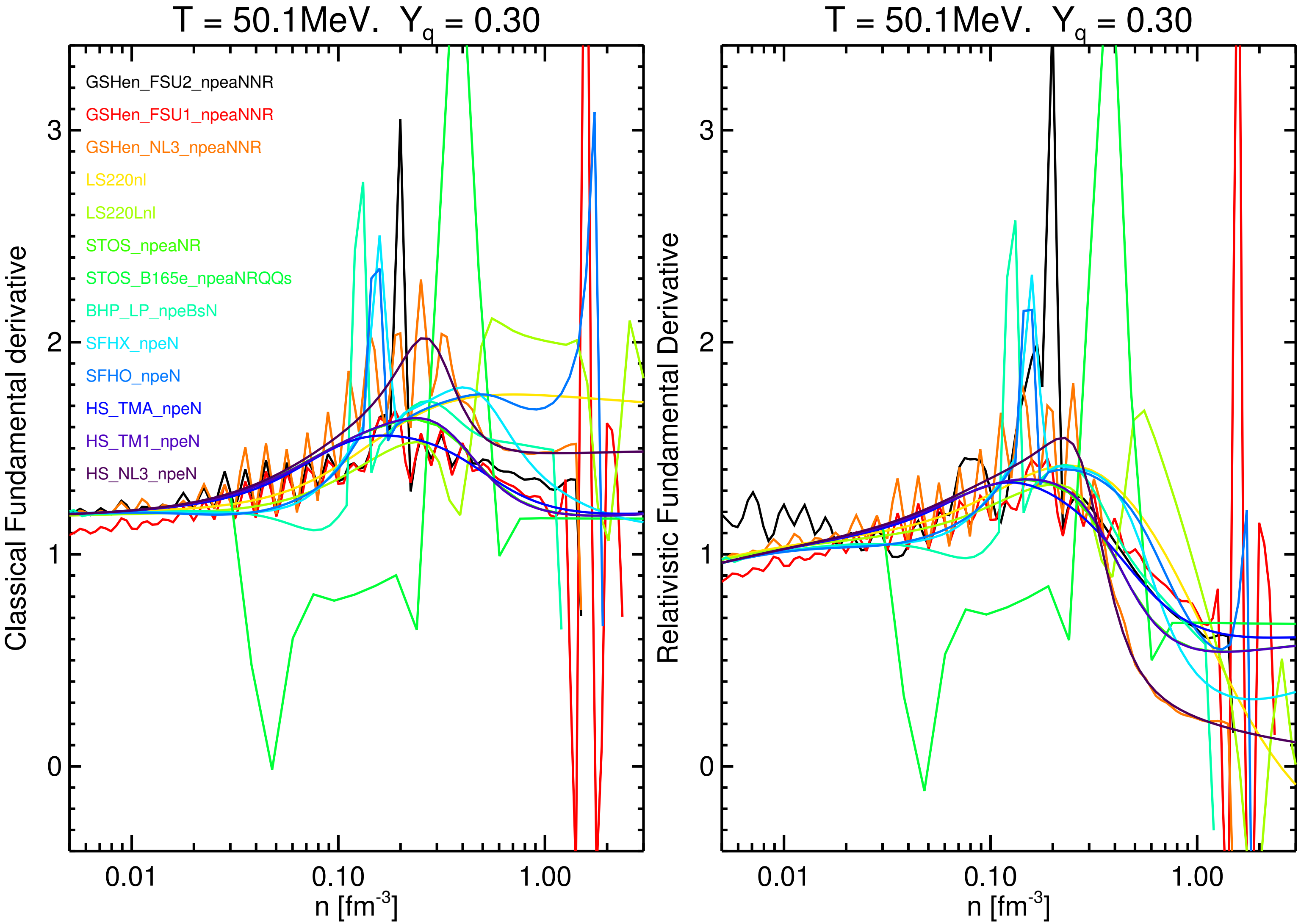
Non-Convexity

In classical fluid dynamics, the convexity of a thermodynamical system is determined by the EOS and, more specifically, by the so-called fundamental derivative (see Isabel's talk):

$$\mathcal{G}_{(\mathrm{cla})} := -\frac{1}{2}\, V\, \frac{\left.\dfrac{\partial^2 p}{\partial V^2}\right|_s}{\left.\dfrac{\partial p}{\partial V}\right|_s}$$

$$\mathcal{G}_{(\mathrm{rel})} = \mathcal{G}_{(\mathrm{cla})} - \frac{3}{2}\, c^2_{s_{(\mathrm{rel})}} \ .$$

Non-Convexity



Motivated by the indications of the existence of possible regions in the dense-matter EOS where the thermodynamics can be non-convex, we performed a numerical study of the structure and dynamics of compact stellar configurations described by a BZT fluid.

For our study we consider the dynamics of unstable and uniformly-rotating neutron stars that collapse gravitationally to black holes.

A phenomenological NC EOS

We choose a particularly simple form of the EOS, namely an ideal gas EOS with an adiabatic index which depends on the density. While this phenomenological EOS can only be regarded as a toy-model, it serves nonetheless to exemplify the particularities that appear when the EOS is non-convex.
The pressure p obeys an ideal-gaslike EOS of the form, GGL-EOS (Gaussian Gamma Law):

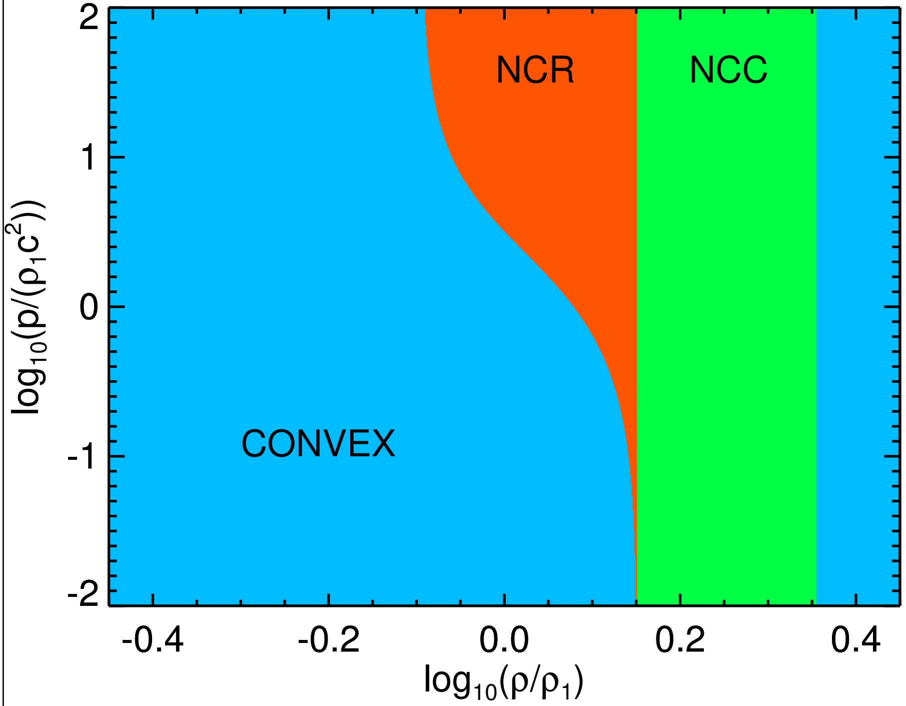
$$p = (\gamma - 1)\rho\epsilon$$

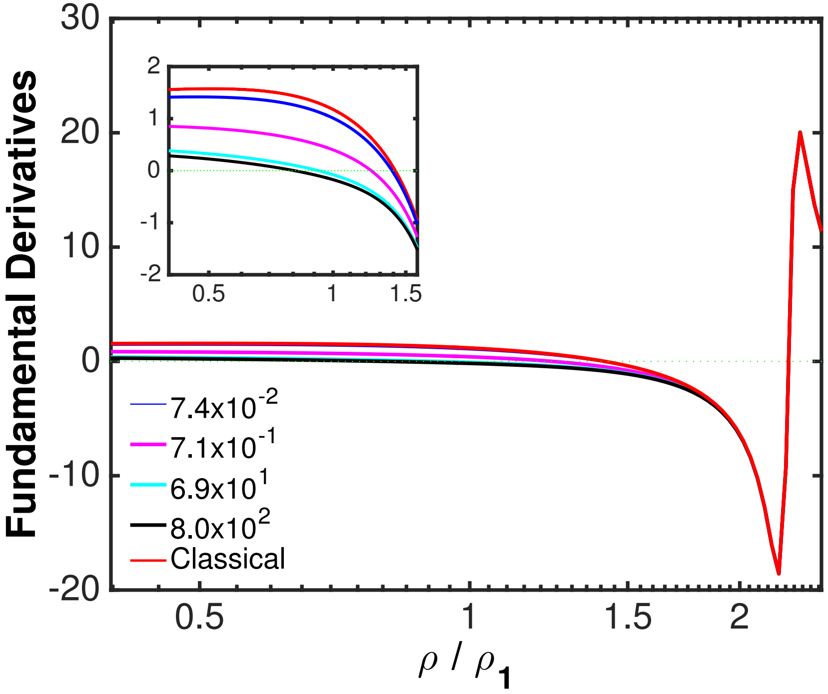
$$\gamma \equiv \gamma_0 + \mathcal{K} \exp\left(-\frac{x^2}{\sigma^2}\right) ,$$

$$\mathcal{K} := \gamma_1 - \gamma_0 , \quad x := \rho - \rho_1$$

GGL-EOS

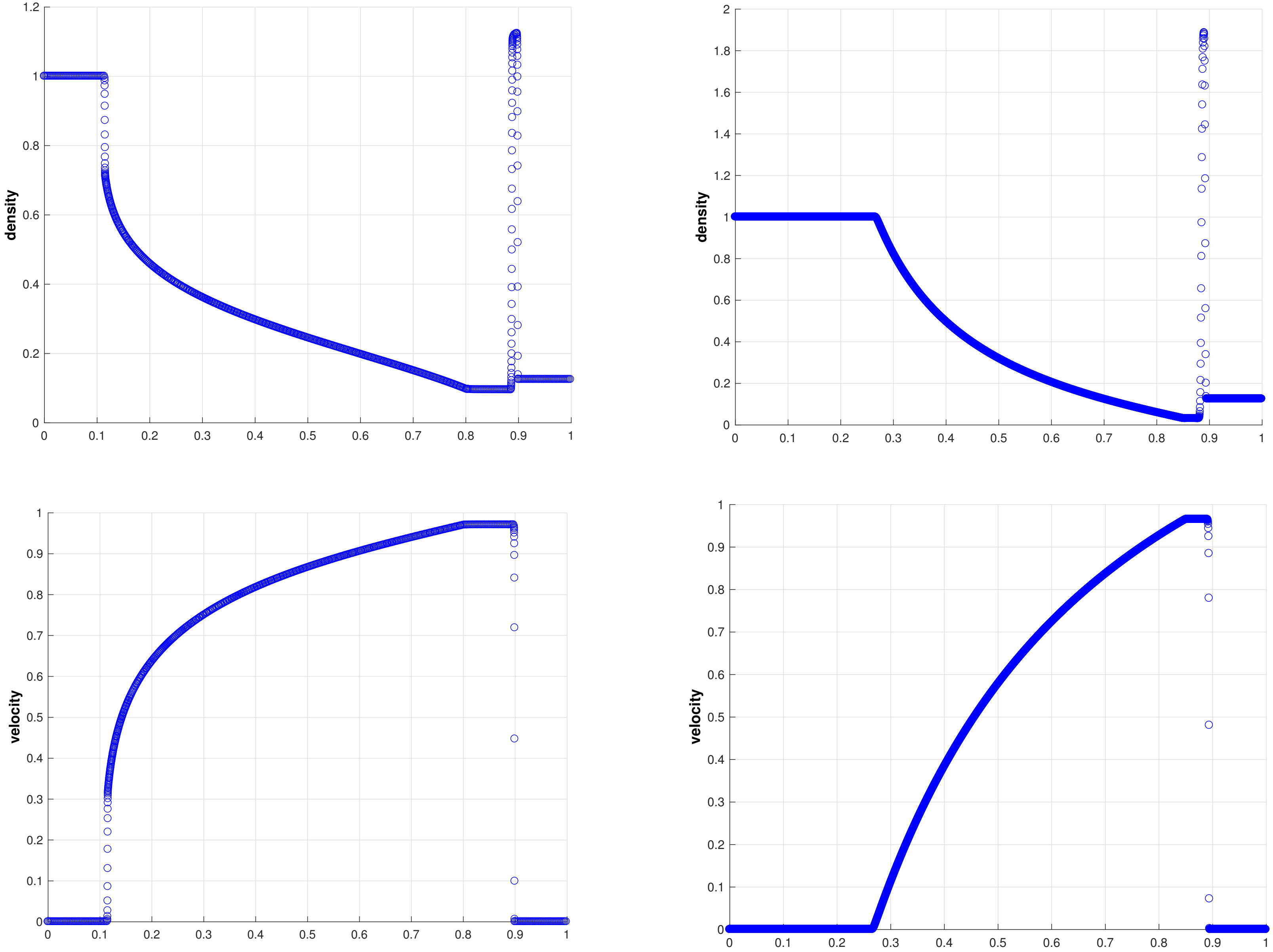
$$\gamma_1 = 1.9, \gamma_0 = 4/3, \sigma = 1.1, \rho_1 = 10^{15}\mathrm{g/cm}^3$$





The FD becomes negative -> **Non convex region!**

Relativistic blast wave test



Gravitational collapse of RNS

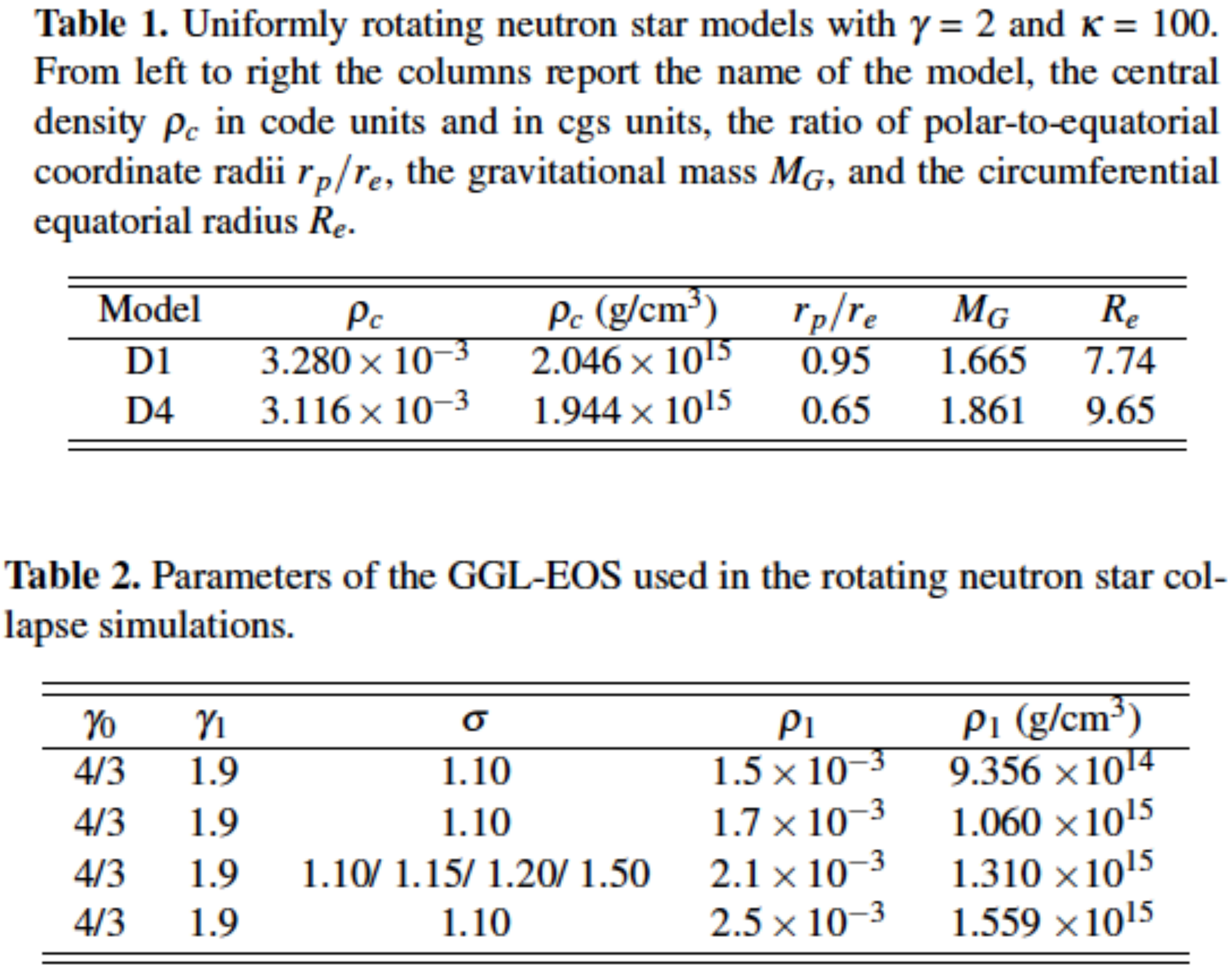


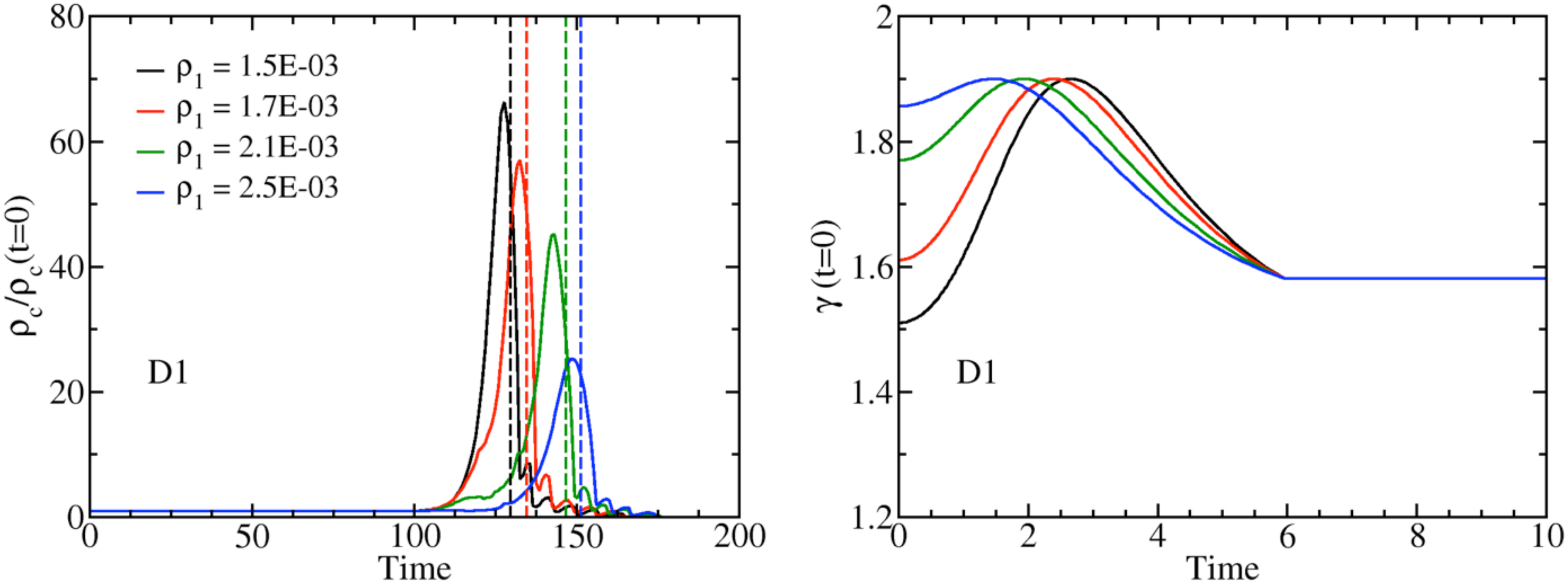
Table 1. Uniformly rotating neutron star models with $\gamma = 2$ and $\kappa = 100$. From left to right the columns report the name of the model, the central density ρ_c in code units and in cgs units, the ratio of polar-to-equatorial coordinate radii r_p/r_e, the gravitational mass M_G, and the circumferential equatorial radius R_e.

Model	ρ_c	ρ_c (g/cm^3)	r_p/r_e	M_G	R_e
D1	3.280×10^{-3}	2.046×10^{15}	0.95	1.665	7.74
D4	3.116×10^{-3}	1.944×10^{15}	0.65	1.861	9.65

Table 2. Parameters of the GGL-EOS used in the rotating neutron star collapse simulations.

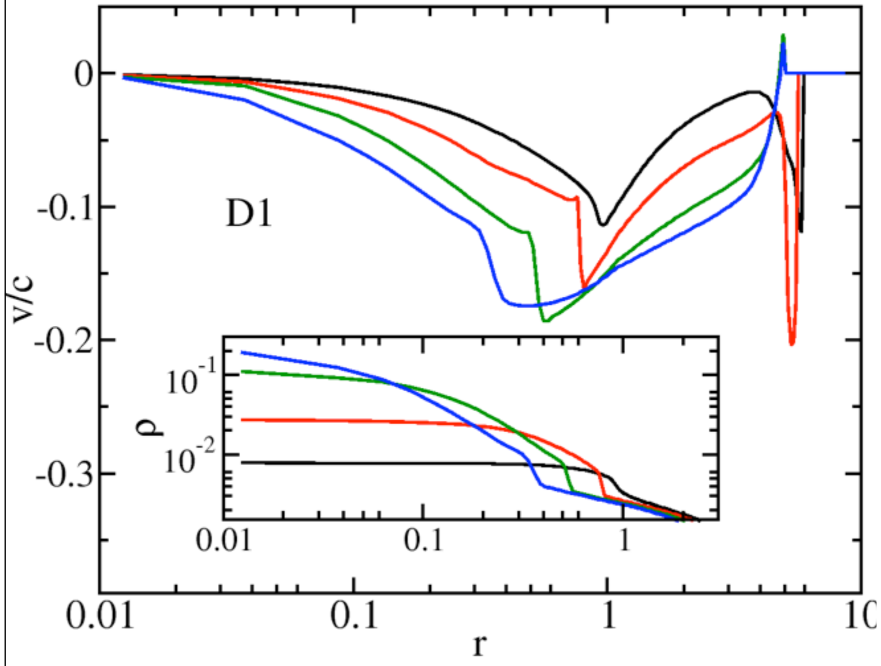
γ_0	γ_1	σ	ρ_1	ρ_1 (g/cm^3)
4/3	1.9	1.10	1.5×10^{-3}	9.356×10^{14}
4/3	1.9	1.10	1.7×10^{-3}	1.060×10^{15}
4/3	1.9	1.10/ 1.15/ 1.20/ 1.50	2.1×10^{-3}	1.310×10^{15}
4/3	1.9	1.10	2.5×10^{-3}	1.559×10^{15}

Gravitational collapse of RNS

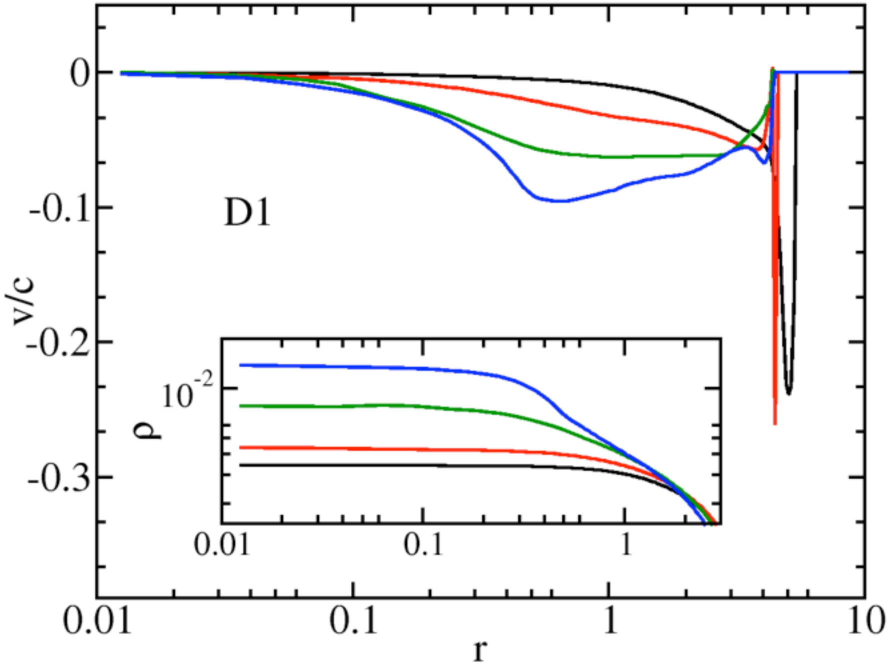


Gravitational collapse of RNS

$\rho_1 = 1.5E-3$

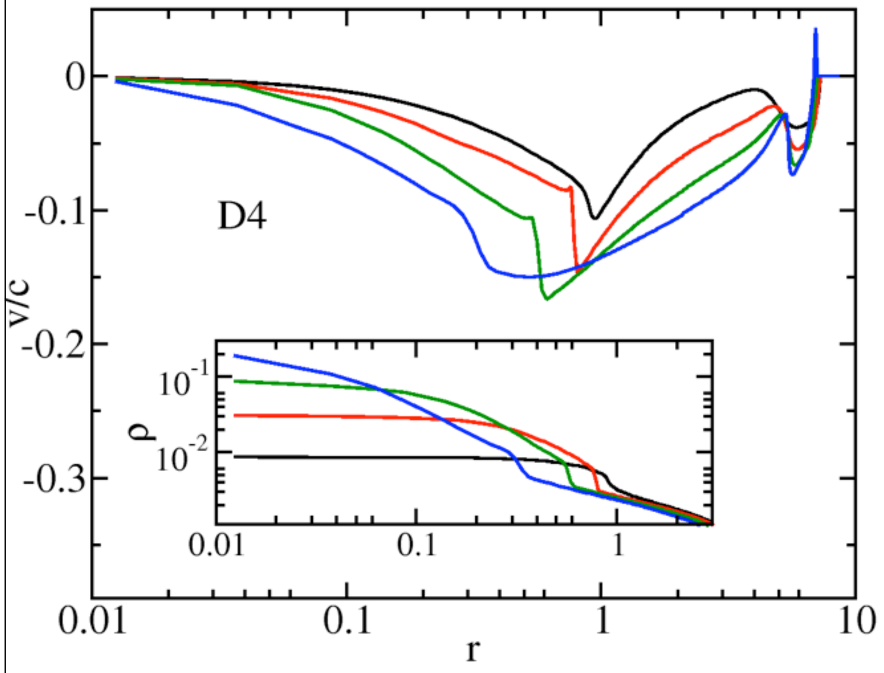


$\rho_1 = 2.5E-3$

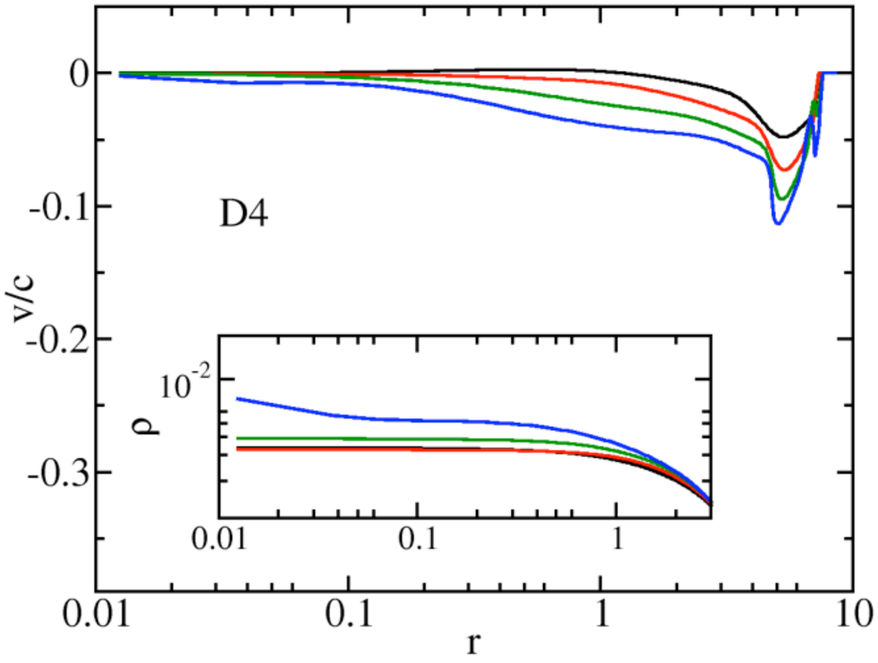


Gravitational collapse of RNS

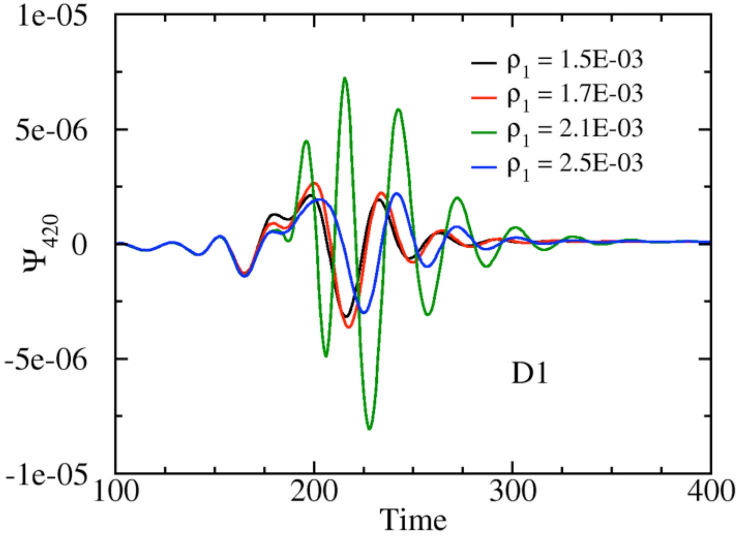
$$\rho_1 = 1.5E-3$$

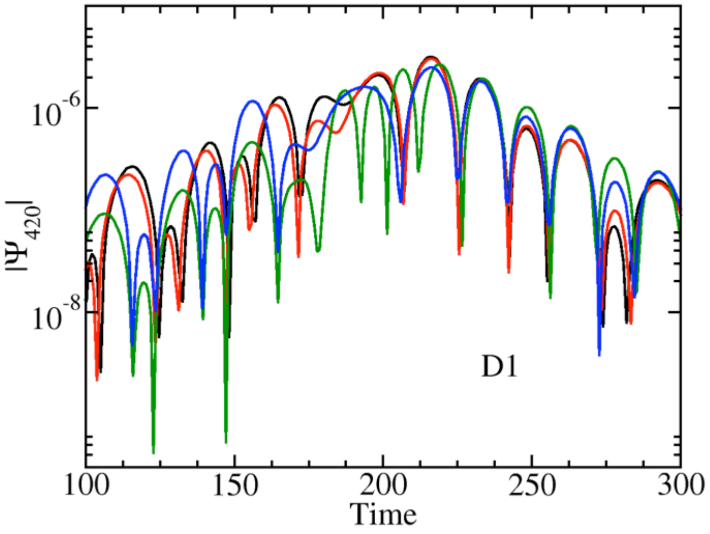


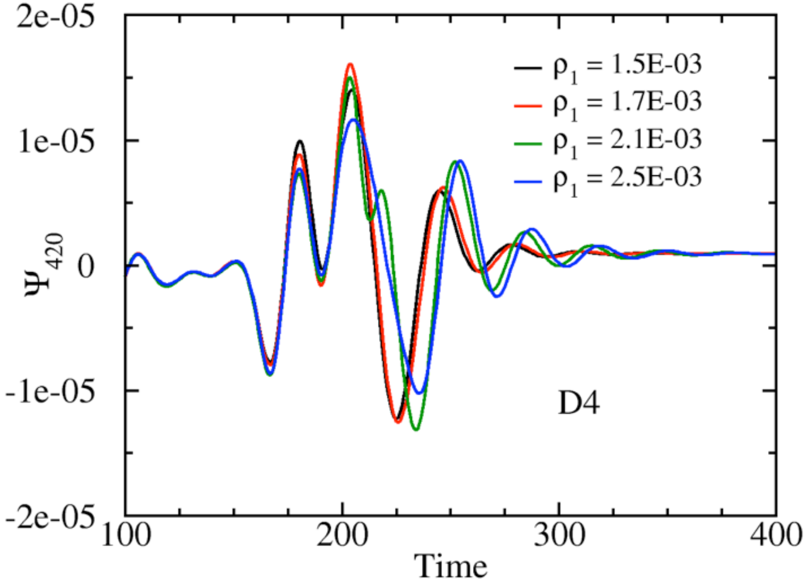
$$\rho_1 = 2.5E-3$$



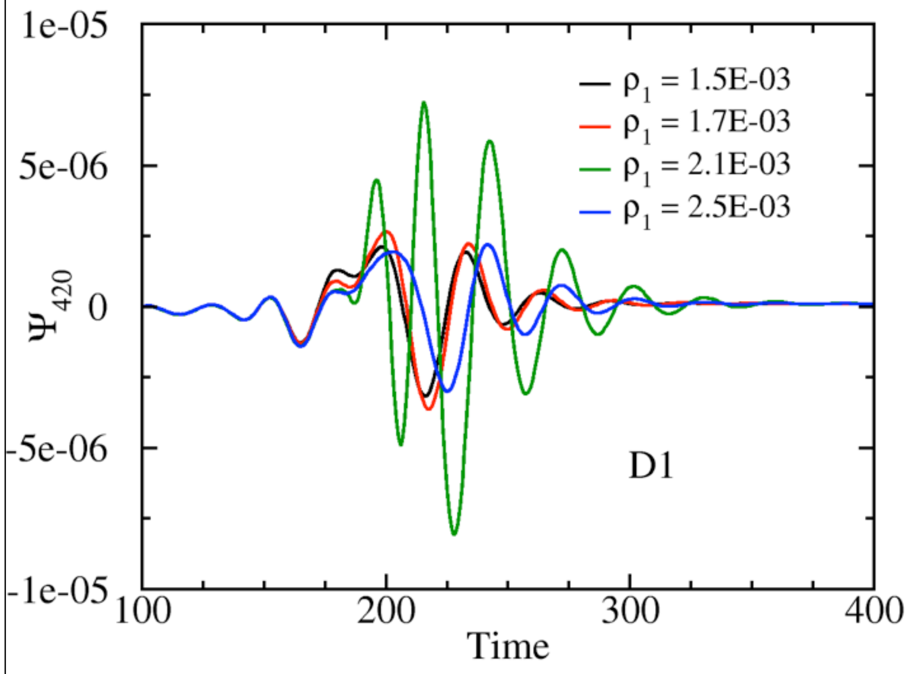
Gravitational wave radiation

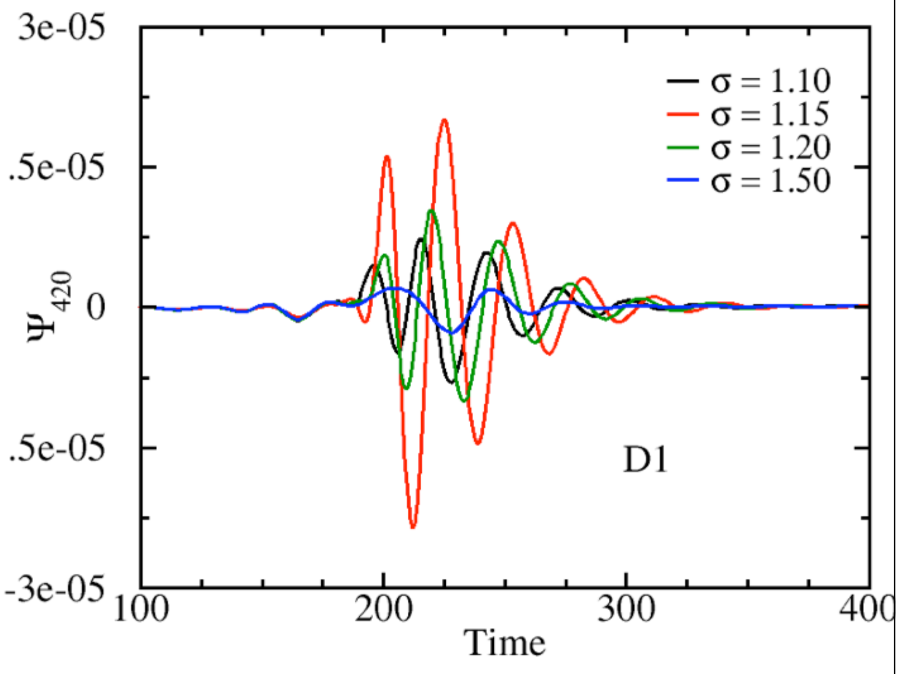






Gravitational wave radiation





Fixed width:

$$\sigma = 1.1$$

Fixed density parameter:

$$\rho_1 = 2.1\mathrm{E} - 3$$

Summary

- The EOS of high-density matter might contain regions in which the thermodynamics may be non-convex. The so-called BZT flows are subject to non-convex dynamics and are characterized by the appearance of compound waves (rarefaction shocks) during the evolution.

- We have chosen a simple, phenomenological, non-convex EOS, namely an ideal-gas EOS with an adiabatic index which depends on the density.

- The numerical simulations of collapsing stars have shown the appearance of the characteristic compound waves of BZT fluids and have also illustrated how the non-convex dynamics is also imprinted on the gravitational-wave signals associated with the infalling phase.

- A future study using actual microphysical EOS from nuclear physics will be presented elsewhere.