Simulating Differentially Rotating Hybrid Stars

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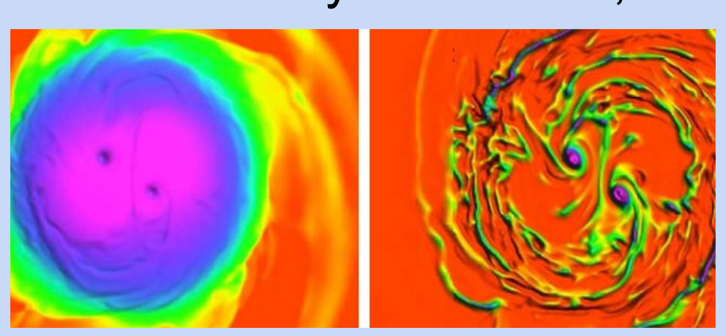
Abstract

Our goal is to understand how deconfinement phase transitions effect the evolution of non-axisymmetric fluid instabilities like the one-arm spiral instability. Studies have shown [3] that when these non-axisymmetric instabilities develop, they can affect the gravitational waves produced by the merger remnants. We are running general relativistic hydrodynamic simulations of differentially rotating stars, that have the potential to be a model for post merger remnants.

One-Arm Spiral Instability

The one-arm Spiral Instability develops when vortices created by the merger cause a toroidal fluid configuration where the maximum density occurs in a ring around the center-of-mass. The images below show a color map of $\rho_{e_{max}}$ (the equatorial rest-mass density (left) and Ω_{xy} (right) at a select time after the NS collision. When the instability saturates, the m = 1 mode dominates.



East, William E., et al. "Relativistic simulations of eccentric binary neutron star mergers: one-arm spiral instability and effects of neutron star spin." [2]

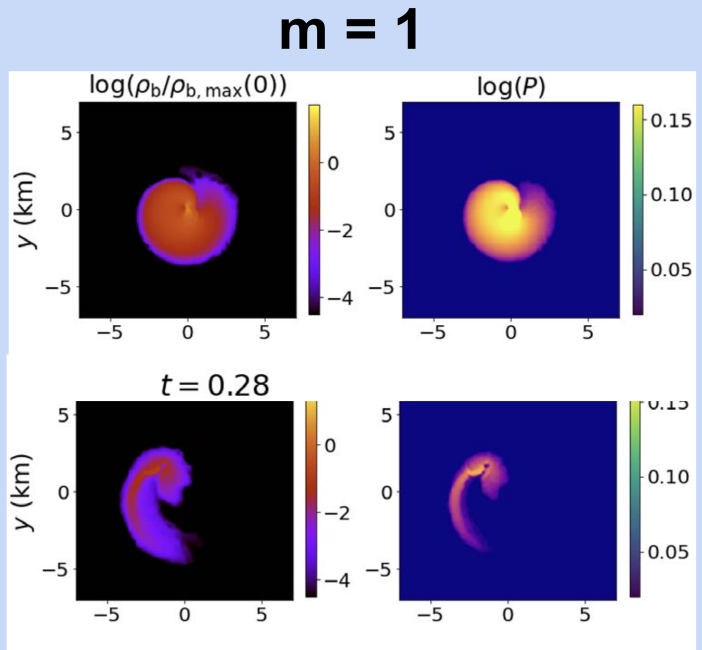
Density Perturbation

Our goal was to excite the one arm spiral instability explicitly within the simulation. In order to break angular symmetry in such a way, we initiated a density perturbation in the azimuthal direction defined by the added density term below.

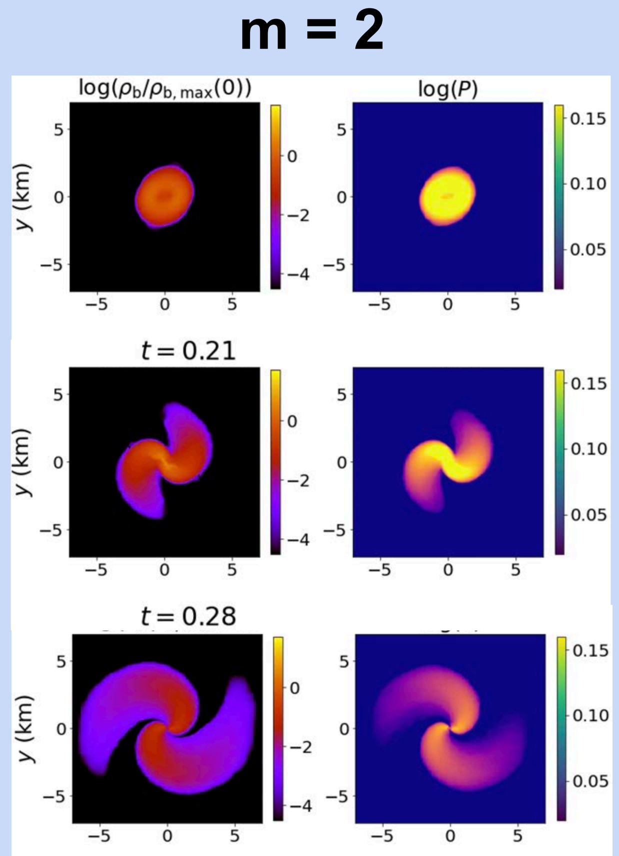
$$\rho_o \longrightarrow \rho_o\left(1 + \mathbf{A}\frac{\omega \sin(\mathbf{m}\phi)}{\mathbf{r_e}}\right)$$

We ran some simulations to test our perturbation for the $m = 1$and $m = 2$ modes. For these tests, we assumed a $\Gamma = 2$ polytrope.

m = 1



m = 2



Methods and GRHD Evolution Code

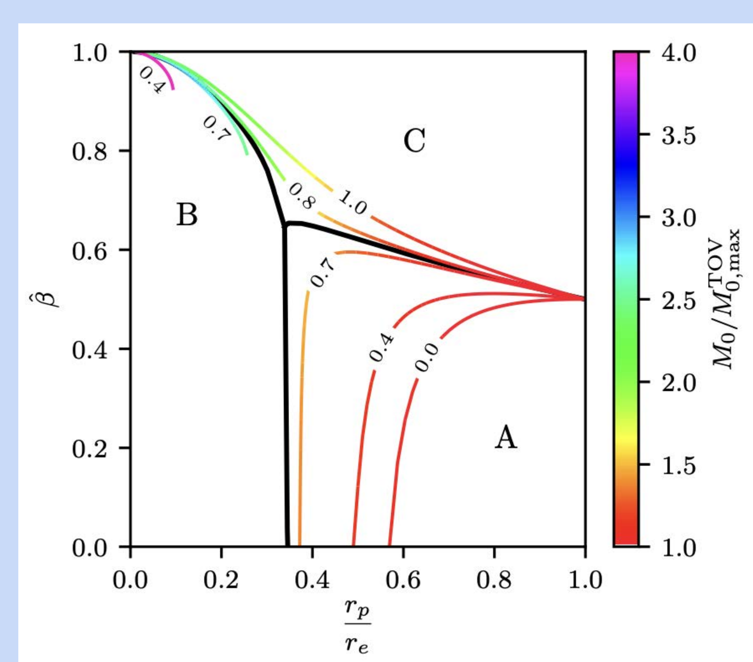
We use IllinoisGRMHD to run the simulations. Illinois GRMHD solves the equations of ideal relativistic-hydrodynamics for each block on a discrete grid. IllinoisGRMHD works with the following stress-energy tensor:

$$T_{\mu\nu} = (\rho_b h + b^2)u_\mu u_\nu + (P + \frac{b^2}{2})g_{\mu\nu} - b_\mu b_\nu$$

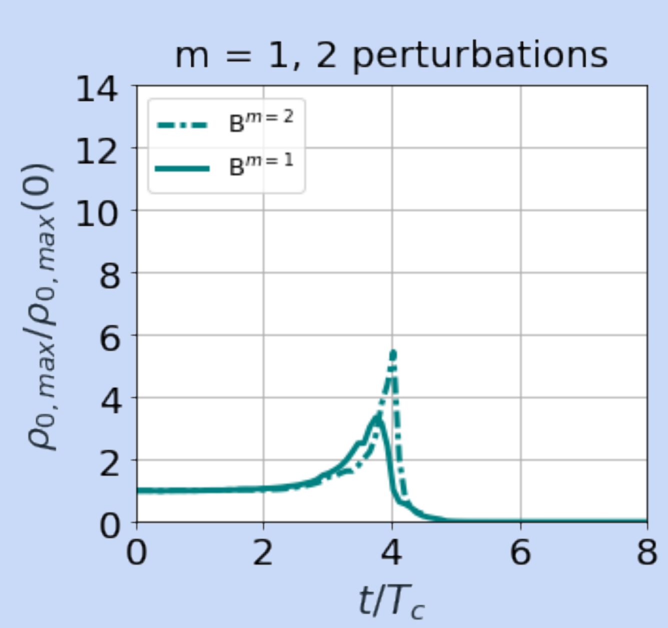
The stress-energy tensor describes the matter and energy content in a system. The form above corresponds to an ideal magnetized fluid which is a magnetized fluid without dissipative interactions (no viscosity, friction, heat transfer, resistivity). This provides the right hand side for Einstein's equations:

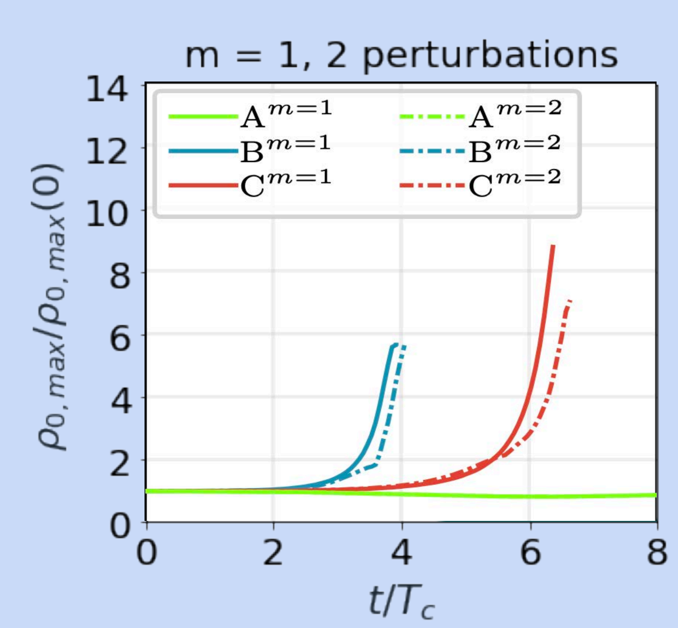
$$\mathbf{G}_{\mu\nu} = 8\pi\mathbf{T}_{\mu\nu}$$

The IllinoisGRMHD code allows for the use of finite-temperature EOS tables to run simulations of differentially rotating neutron and hybrid stars. We will construct these differentially rotating models with the Cook code, and consider both spheroidal models (where the maximum density is at the center of the star) and quasi-toroidal models (where the maximum density occurs in a ring around the center of the star).



It has been shown [4] that quasi-toroidal NS configuration can appear as transient states after a BNS merger and that these states are unstable to the one-arm spiral instability. We've classified the models into types A, B, and C, whose distinctions are shown in the solution space for a $\Gamma = 2$ polytope projected on the left.

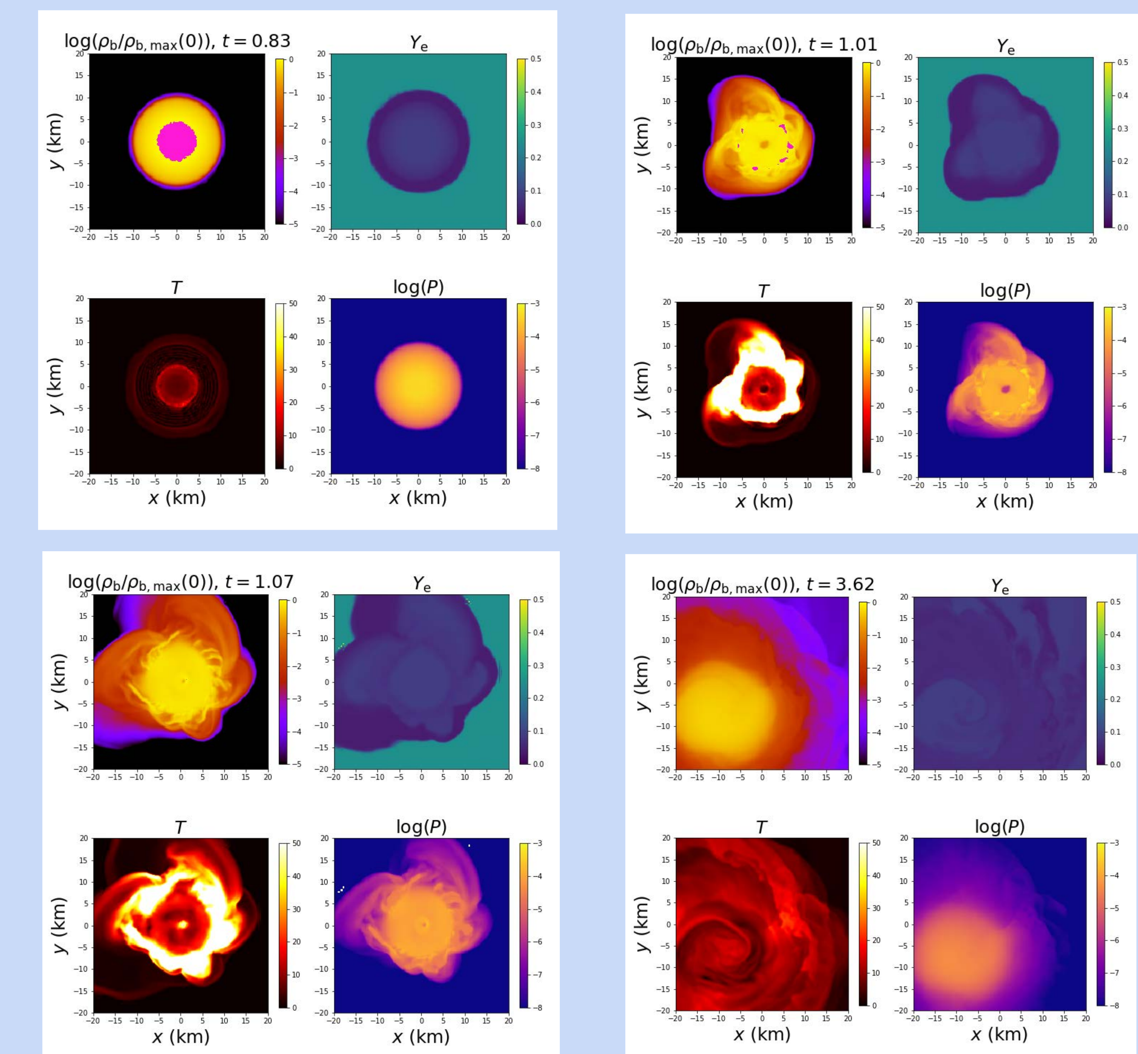




Results

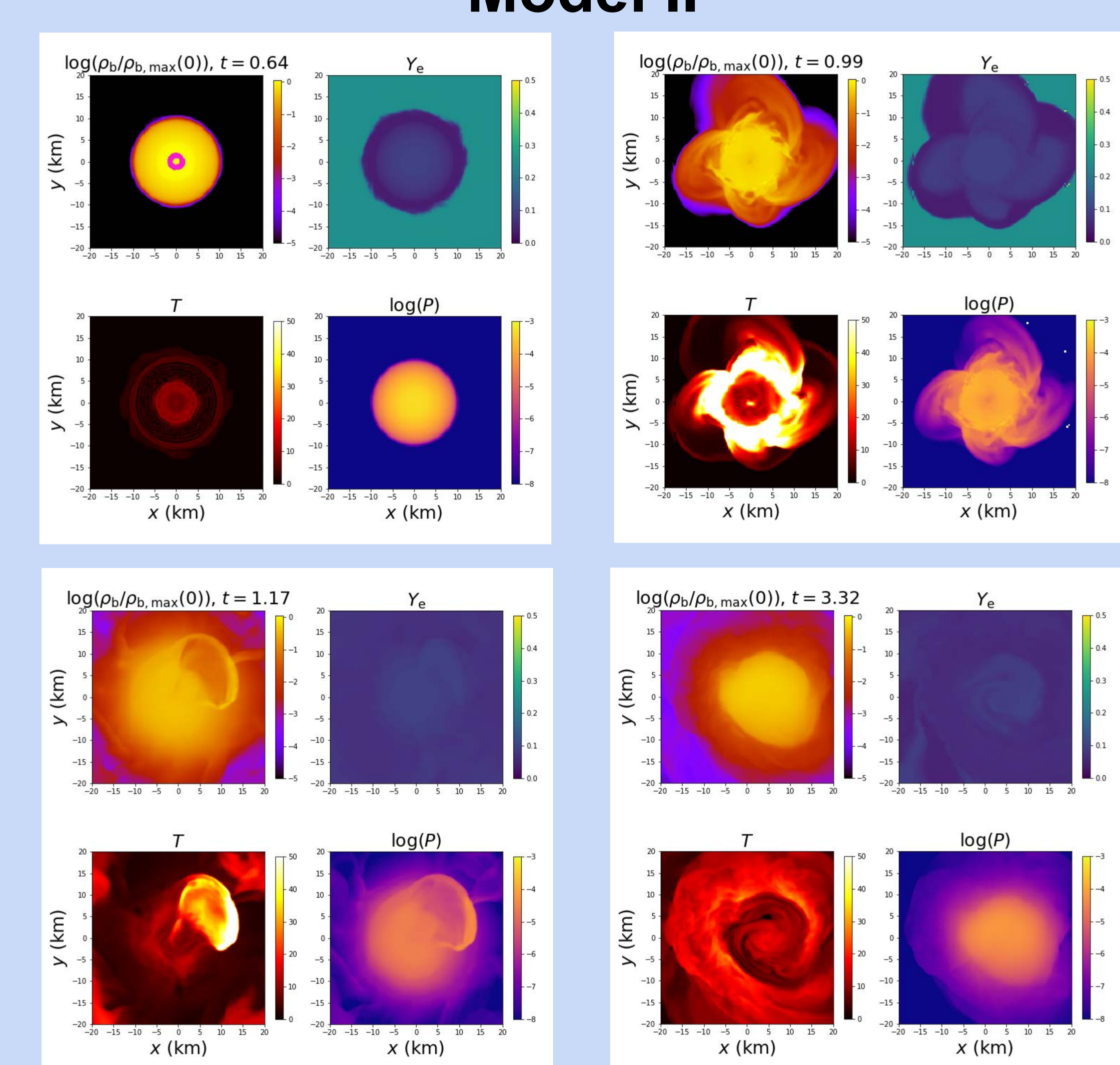
We have built a type C model using the BBKF 1.3 Equation of State. We consider two models with the same mass but different radius. Below are a few snapshots of the various fluid variables within these simulated models. These are equilibrium models without any perturbation to the density.

Model I



Both Type C sims show significant drifts of the center of mass. The development of the one and two-arm spiral instability seemed to be subtly present. In order to determine wether or not modes will in-fact develop, we will introduce the rest-mass density perturbation.

Model II



Results

[1] T. Baumgarte, "Numerical relativity and compact binaries," Physics Reports, vol. 376, pp. 41–131, mar 2003.

[2] W. E. East, V. Paschalidis, F. Pretorius, and S. L. Shapiro, "Relativistic simulations of eccentric binary neutron star mergers: One-arm spiral instability and effects of neutron star spin," Physical Review D, vol. 93, jan 2016.

[3] P. L. Espino, A. Prakash, D. Radice, and D. Logoteta, "Revealing phase transition in dense matter with gravitational wave spectroscopy of binary neutron star mergers," 2023.

[4] P. L. Espino, V. Paschalidis, T. W. Baumgarte, and S. L. Shapiro, "Dynamical stability of quasitoroidal differentially rotating neutron stars," Physical Review D, vol. 100, aug 2019.