IllinoisGRMHD

A compact, user-friendly, and robust GRMHD code

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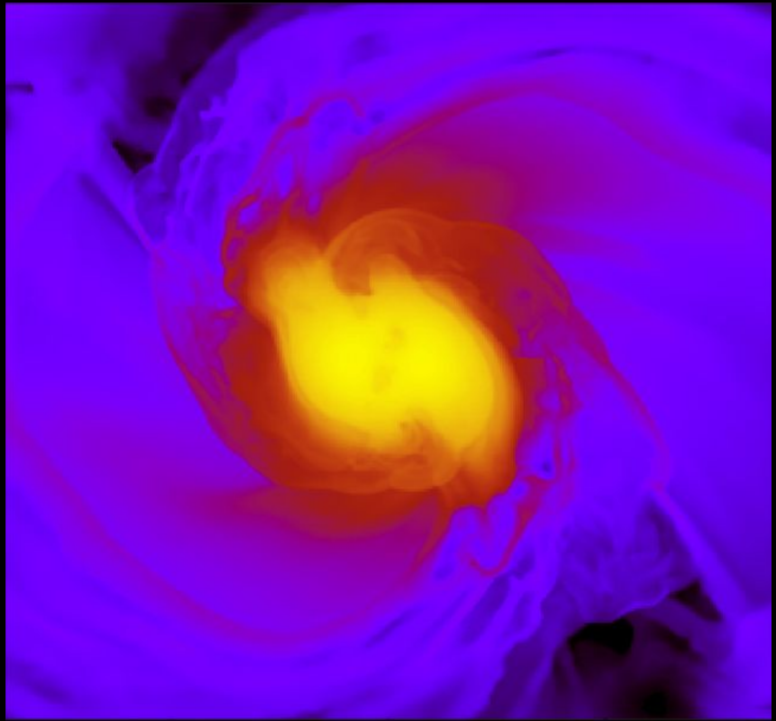


Baryonic density from a magnetized, equal-mass BNS simulation performed with IllinoisGRMHD using a **tabulated EOS**, shortly after merger

Outline

- An overview of the code
- Code development update (LR Werneck, ZB Etienne + TCAN collaboration, in preparation)
  - ↳ Tabulated equation of state (EOS) support
    - ☆ Electron fraction evolution
    - ☆ Entropy evolution
    - ☆ New conservative-to-primitive (C2P) routines
- Latest results
- Summary & future work

An overview of IllinoisGRMHD

- A 2015 rewrite of the original GRMHD code of the Illinois Numerical Relativity Group (https://arxiv.org/abs/1501.07276)
- Roundoff agreement with the original code, while being ~2x faster and containing ~23x less lines of code (from ~70k to <3k)
- GRMHD for dynamical spacetimes, including single neutron stars; binary neutron stars with and without magnetic fields; black hole accretion disks; and many more!
- Open-sourced and available as part of the Einstein Toolkit (https://www.einsteintoolkit.org/)
- Documented in pedagogical Jupyter notebooks available at http://nrpyplus.net (previous TCAN workshop talk)

This talk

- Hybrid, polytropic-based ***and*** fully tabulated EOS support
- Electron fraction and entropy evolution support
- New C2P infrastructure that minimizes spurious heating when using tabulated EOS

Tabulated EOS support

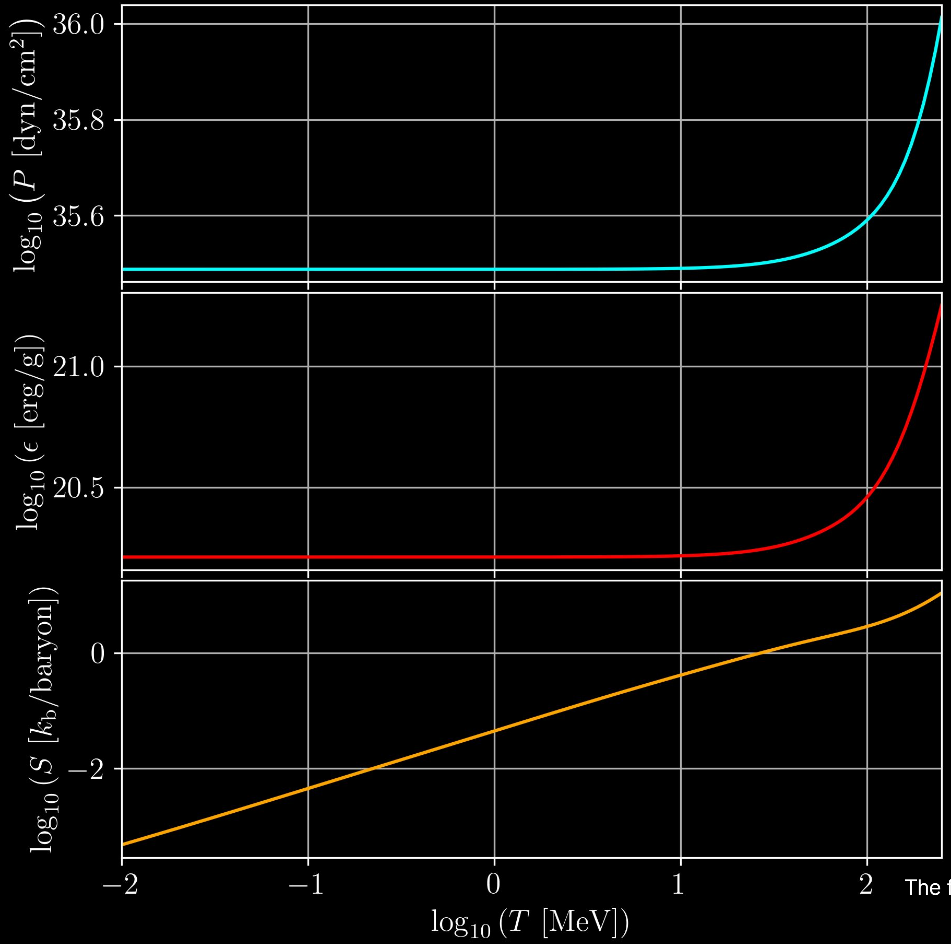
- Provides the most realistic description of neutron stars to date

- The tables typically provide hydrodynamics quantities, such as pressure and specific internal energy, as functions of the baryonic density, electron fraction, and temperature

- Implementation built from open-source and freely available **Zelmani** infrastructure by O'Connor & Ott (available at http://stellarcollapse.org)

- Integration with the Einstein Toolkit through the **EOS_Omni** thorn, with further optimizations

Tabulated EOS support



- In many situations, the temperature becomes an unknown and a table inversion must be performed
- When considering dense, cold matter (as is typical in binary neutron star—BNS—initial data), both the pressure and energy have very weak dependence on the temperature
- Small uncertainties in the input variables can be greatly amplified during a table inversion, leading to large errors in the temperature obtained and ultimately in spurious heating of the stars
- By using the entropy to perform the inversion, this issue is mitigated, but requires the entropy to be evolved alongside the other hydro quantities

The figure uses the LS220 tabulated EOS of O'Connor & Ott, available at http://stellarcollapse.org. The density is fixed at 1e15 g/cm^3 and electron fraction is fixed at 0.1.

New evolved variables

$$\nabla_\mu \left(n_\mathrm{b} u^\mu \right) = 0$$

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu F^{*\mu\nu} = 0$$

Standard GRMHD equations

$$\nabla_\mu \left(n_\mathrm{e} u^\mu \right) = 0$$

$$\nabla_\mu \left(S u^\mu \right) = 0$$

Additional evolution equations

The electron fraction, $Y_\mathrm{e} \equiv n_\mathrm{e} / n_\mathrm{b}$, and entropy, S are new primitive variables

Conservative-to-primitive (C2P)

- GRMHD equations are written in **conserved** form $\partial_t \vec{C} + \nabla_i \vec{F}^i = \vec{S}$

$$\vec{P} = \begin{bmatrix} \rho_\mathrm{b} \\ T \\ Y_\mathrm{e} \\ P \\ S \\ v^i \\ B^i \end{bmatrix} \xrightarrow{\text{Trivial, analytic}} \vec{C} = \begin{bmatrix} \tilde{D} \\ \tilde{\tau} \\ \tilde{S}_i \\ \tilde{B}^i \\ \tilde{Y}_\star \\ \tilde{S}_\star \end{bmatrix} = \sqrt{\gamma} \begin{bmatrix} D \\ \tau \\ S_i \\ B^i \\ Y_\star \\ S_\star \end{bmatrix} = \sqrt{\gamma} \begin{bmatrix} W\rho_\mathrm{b} \\ \alpha^2 T^{00} - W\rho_\mathrm{b} \\ \alpha T^0{}_i \\ B^i \\ DY_\mathrm{e} \\ WS \end{bmatrix}$$

$\vec{P} \xleftarrow{}\ \vec{C}$: Complicated, non-linear expressions: must use root-finding algorithm

New C2P infrastructure

- New infrastructure is based on the open-sourced implementation of Siegel *et al.* (available here)

- Primitive recovery with tabulated EOS involves determining the temperature from other primitives through a table inversion

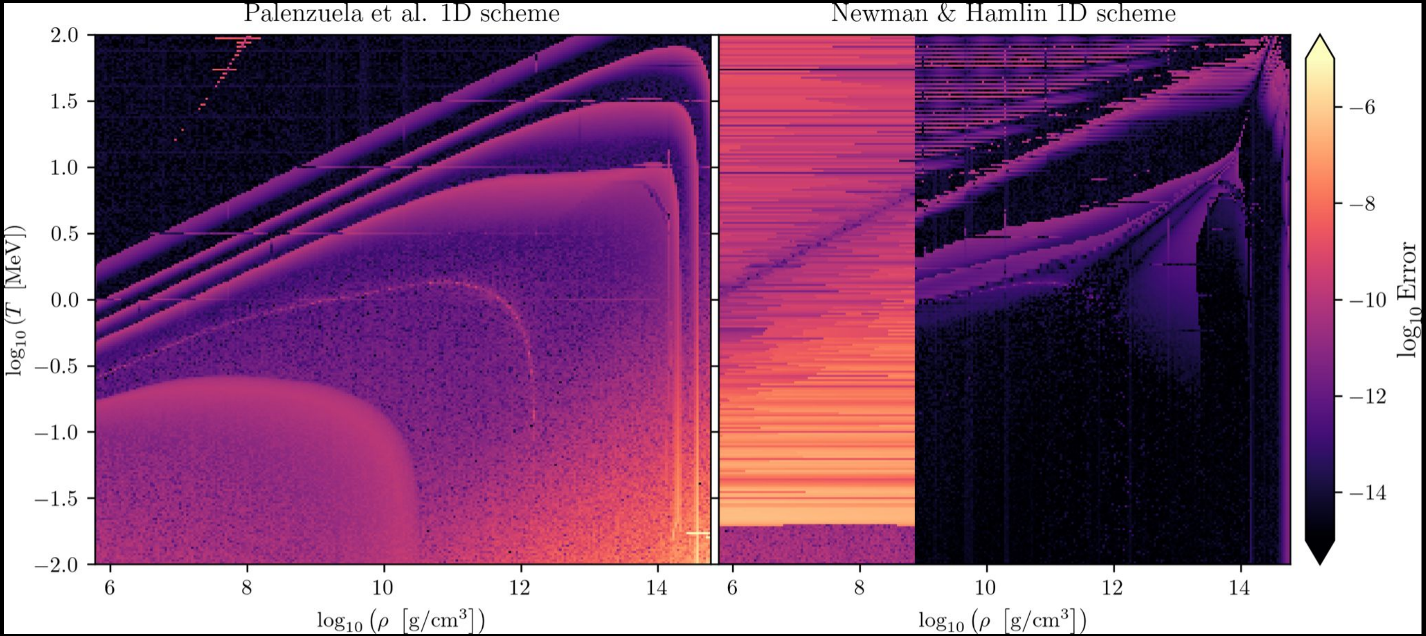
- In **IllinoisGRMHD** we do not have good guesses for the primitives because we do not keep values of the primitives from the previous time step

- Routines that rely on a Newton-Raphson root-finding algorithm do not work well because of this

- Solution: use 1D routines of Palenzuela *et al.* and Newman & Hamlin

- We have modified these routines to use the **entropy** instead of the **specific internal energy** whenever the latter depends weakly on the temperature

New C2P infrastructure: primitive recovery test



$$N_{\rho_b} = N_T = 2^8,\ Y_e = 0.1,\ W = 2,\ \log_{10}\left(P_{\rm mag}/P\right) = -5$$

$$\text{Error} = \sum_i \left|\frac{p_i^{\rm out} - p_i^{\rm in}}{p_i^{\rm out}}\right| \qquad p_i = \left(\rho_b, T, P, \epsilon, v^i, B^i\right)$$

100% primitive recovery success rate for this test!

New C2P infrastructure: backup strategies

• While the routines work perfectly in controlled tests, during an actual BNS evolution where billions of primitive recoveries are necessary, we are bound to have recovery failures

• These failures are monitored constantly and are **never** expected to happen in a high density region (e.g. the interior of a NS). If such a failure occurs, the run is terminated.

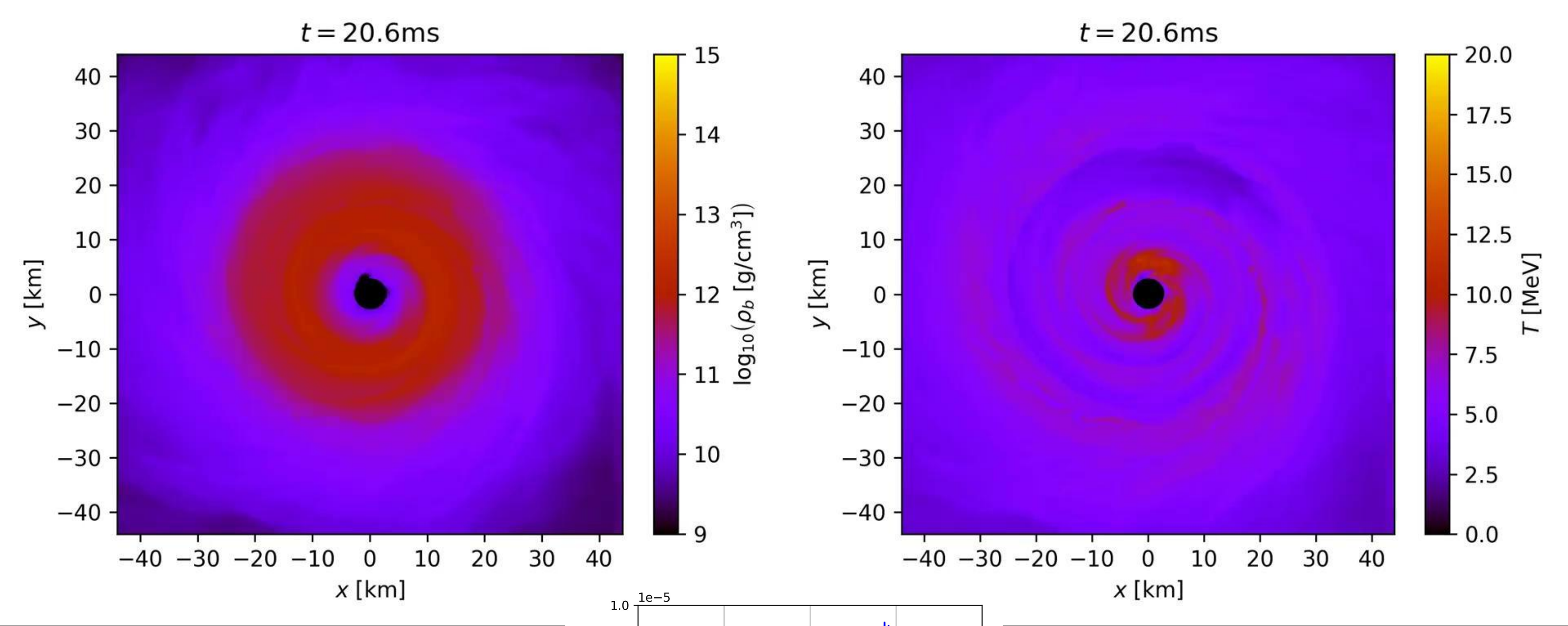
• However, failures can (and will) happen, in the artificial atmosphere

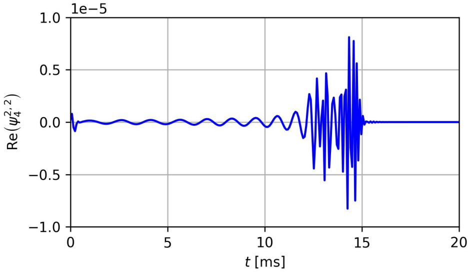
• Whenever such failures happen, we attempt up to 4 additional recoveries after changing the **conserved** variables to

$$C_{\text{new}} = (1-w)C_{\text{orig}} + w\bar{C}_{\text{neighbors}} \ , w = \frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1$$

• If we are still not able to recover the primitives after all these attempts (which is very rare), we reset the primitives to their atmospheric values and the fluid 3-velocity to zero

Magnetized, equal-mass BNS results with tabulated EOS





- Equal-mass (1.39 solar masses)
- 45km initial separation $\log_{10}(P_{\rm mag}/P) = -4$
- Magnetized,

- Initial data produced by Tanmayee Gupte using LORENE (for more details see her talk tomorrow!)

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Summary & future work

- **IllinoisGRMHD** has been updated to have:
  - Tabulated EOS support
  - New C2P routines
  - Electron fraction evolution
  - Entropy evolution
- See Fede Armengol's talk on Thursday for more information on the post-merger phase of our runs and the "hand-off" to **HARM3D**!
- Adding neutrino physics to **IllinoisGRMHD** is a work in progress