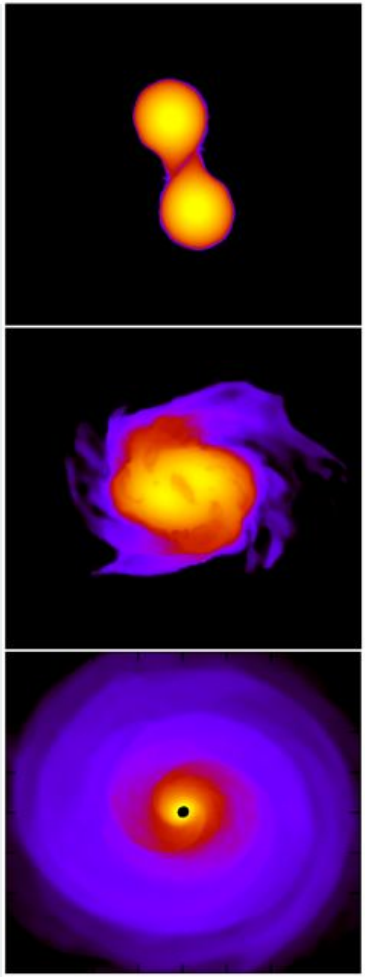
The Hand-Off Package

Federico G Lopez Armengol

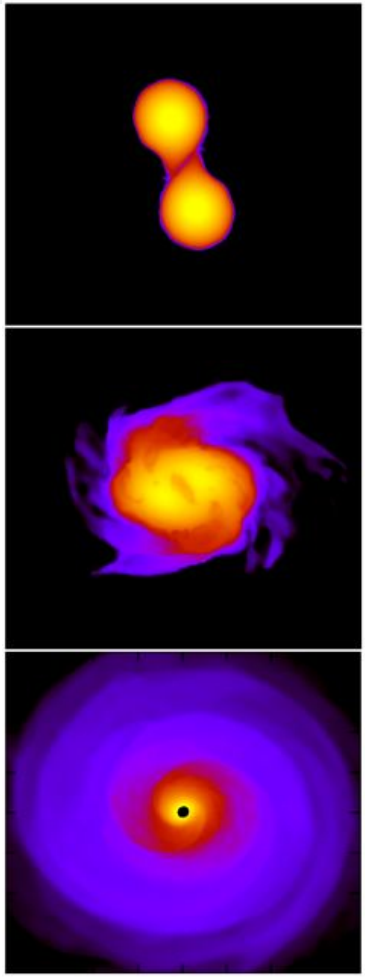
On behalf of the TCAN Collaboration



Context and Motivation

BNS mergers are one of the most interesting systems in the Universe:

- Copious amount of GW, sensible to ground-based detectors.
- Information about NS tidal deformability and masses, crucial for understanding high-density EoS, NS structure and EM fields.
- Substantial part of r-process elements in the Universe are synthesized within the associated the kilonova remnant.
- Candidates for explaining sGRBs.
- Shed light on the formation process and population of binary systems.
- ...

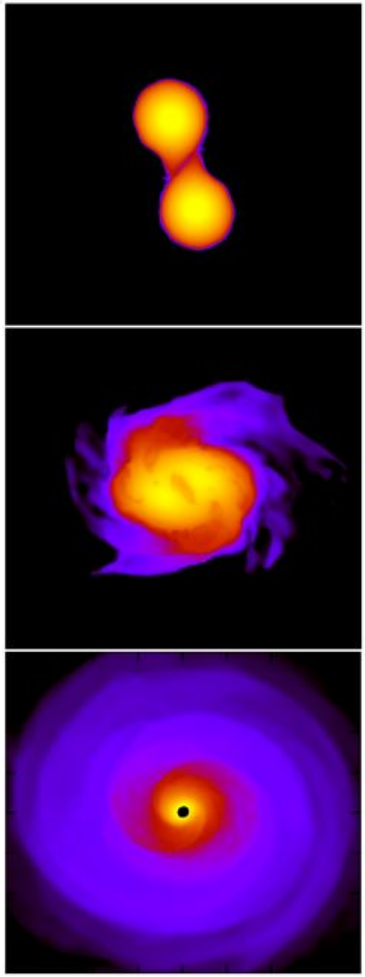


Context and Motivation

BNS mergers involve great variety of physical processes: nuclear equations of state, nucleosynthesis, general relativity, neutrino transport, photon transport, magnetohydrodynamics.

A realistic simulation of a BNS pre and post-merger is unfeasible for a single code. Current models focus on a subset of the relevant physics.

On the TCAN Collaboration we accept this physical complexity and face it with an heterogeneous set of codes, handing off data consistently among them.

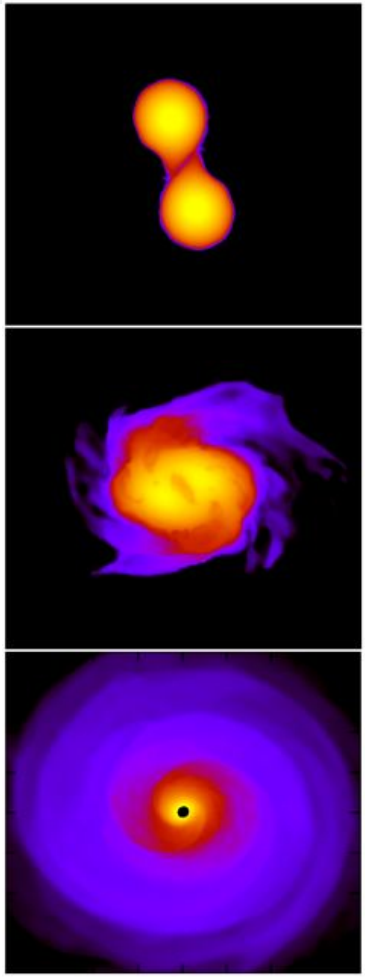


Context and Motivation

Post-merger models can only be initialized with approximate representations: constant specific angular momentum and entropy, ordered poloidal magnetic fields, axisymmetry, among others simplifications.

On the other hand, realistic post-merger datasets inherit Cartesian coordinates from *Numerical Relativity* codes.

The Handoff Package translates the final output of a code designed for BNS merger, to initial data for a code designed for post-merger evolutions.



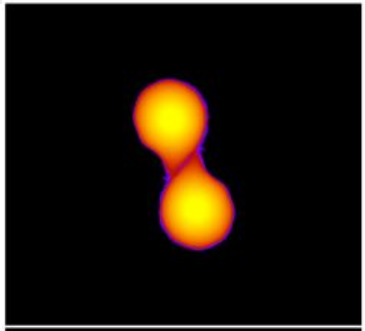
Codes involved

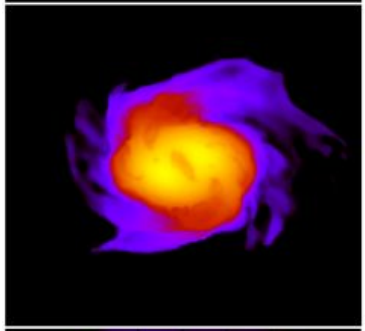
`IllinoisGRMHD (IGM)`

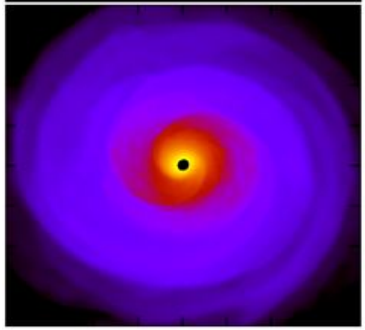
Numerical Relativity code for evolving magnetized BNS inspiral and merger.
Works on Cartesian-AMR grids.
Implementing Ye evolution, realistic nuclear EoS, and neutrino-matter coupling.

`HARM3D`

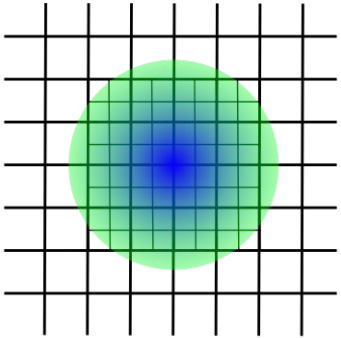
GRMHD code for arbitrary static spacetimes, or even time-dependent prescriptions.
Highly flexible on grids and coordinate systems.
Implementing Ye evolution, realistic nuclear EoS, and neutrino-matter coupling.







Overview of the Hand-Off Package



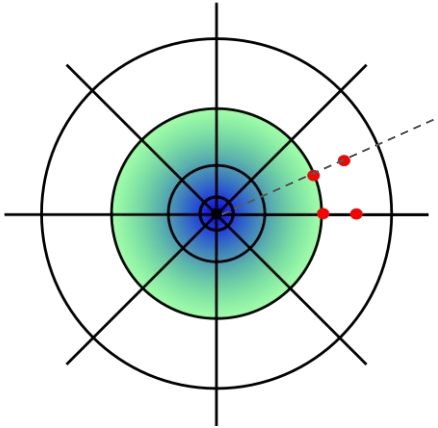
Involves a coordinated set of routines within `IGM`, standalone scripts, and `HARM3D`:

Step0: Get destination grid.

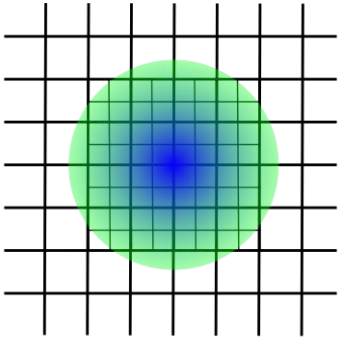
Step1: Interpolate metric and primitives from `IGM`.

Step2: Parse and arrange data.

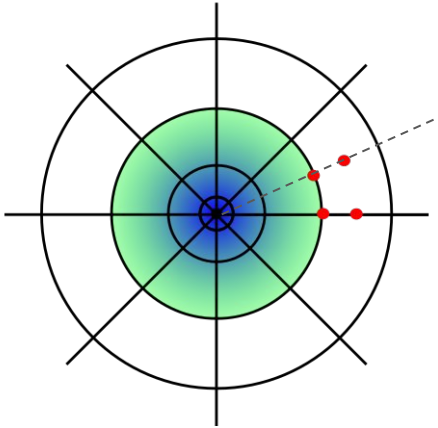
Step3: Initialize `HARM3D`.



Step0: Get destination grid

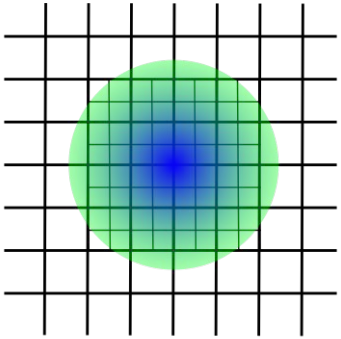


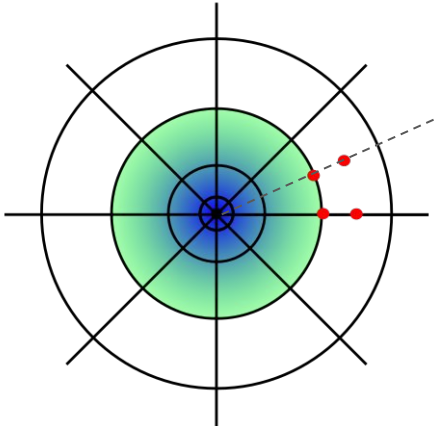
- Design grid based on symmetries and resolution requirements.
- Implement desired grid on HARM3D.
  E.g.:
  $$r\left(x^{1'}\right) = \exp\left(x^{1'}\right), \ \theta\left(x^{2'}\right) = \theta_{\mathrm{c}} + h\sin\left(2\pi x^{2'}\right)$$
- Dump Cartesian coordinates of centers, faces, and corners of every cell.
- Arrange data in binary format, as expected from the following routines in `IGM`.



Step 1: Interpolate metric and primitives

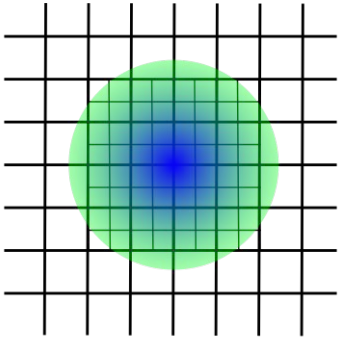
- `IGM` routines read Cartesian positions of destination cells, and interpolate the evolved grid functions to such positions.
- Fourth order interpolation is used for geometrical functions, while first, second, and fourth order for MHD primitives.
- Arrange the interpolated values of every grid function, on every position, on a file with binary format.

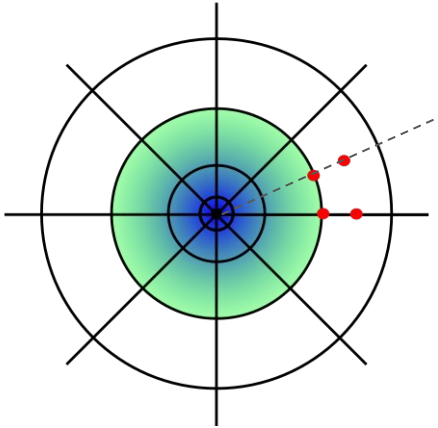




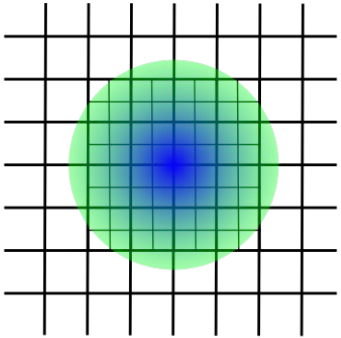
Step 2: Parse and arrange data

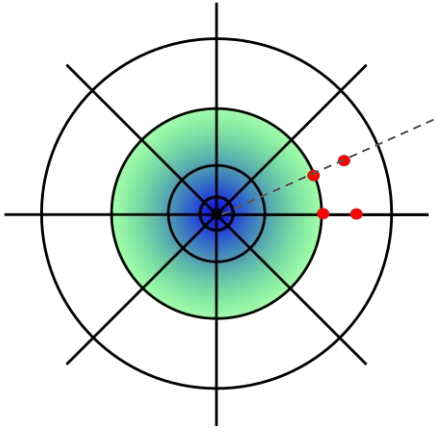
- A standalone script reads in handed off dataset and parse the values of each grid function and position.
- The same script arranges the data in a format that mimic a restart file from `HARM3D`.
- Selective interpolation order for MHD variables in each position.





Step 3: Initialize HARM3D





- Set the same grid on HARM3D.
- Read in the handed off data as restart file with adapted routines.
- Since tensor functions are still on a Cartesian base, we transform to numerical coordinates:

$$g_{\mu'\nu'} = \frac{dx^{\alpha}_{\mathrm{C}}}{dx^{\mu'}}\frac{dx^{\beta}_{\mathrm{C}}}{dx^{\nu'}}g_{\alpha\beta}, \quad v^{\mu'} = \frac{dx^{\mu'}}{dx^{\alpha}_{\mathrm{C}}}v^{\alpha}, \quad A^{\mu'} = \frac{dx^{\mu'}}{dx^{\alpha}_{\mathrm{C}}}A^{\alpha}$$

- Numerical calculation of spacetime connection functions.

Hand-Off:
Fishbone-Moncrief disks

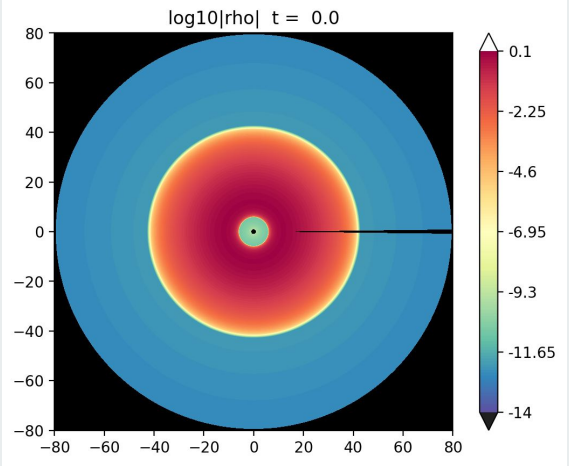
FM Comparison Test

1. We construct the same ID for both `IGM` and `HARM3D`: Axisymmetric torus in hydro-equilibrium *a la* Fishbone & Moncrief (1976), in spherical-KS coordinates, just hydro, with
$$M_{\rm BH} = 1,\ a_{\rm BH} = 0.9375$$
$$r_{\rm in} = 6,\ r_{\rm Pmax} = 12$$
$$P = \kappa\rho^{\Gamma},\ \kappa = 10^{-3},\ \Gamma = \{4/3,\ 2\}$$

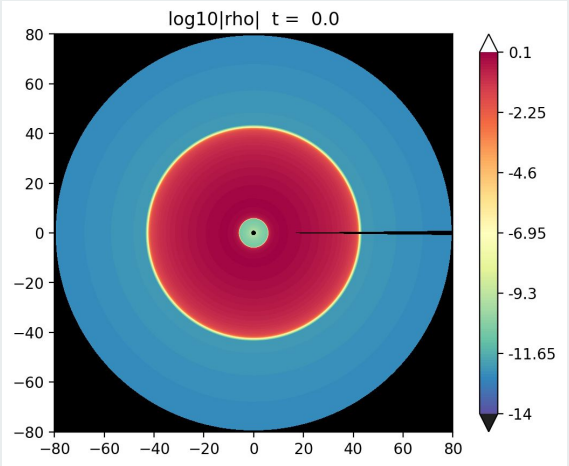
2. Handoff the ID (hydro and geometric functions) from `IGM` to `HARM3D`.

3. Evolve the handed off data in `HARM3D` and compare with the original run in `HARM3D`.

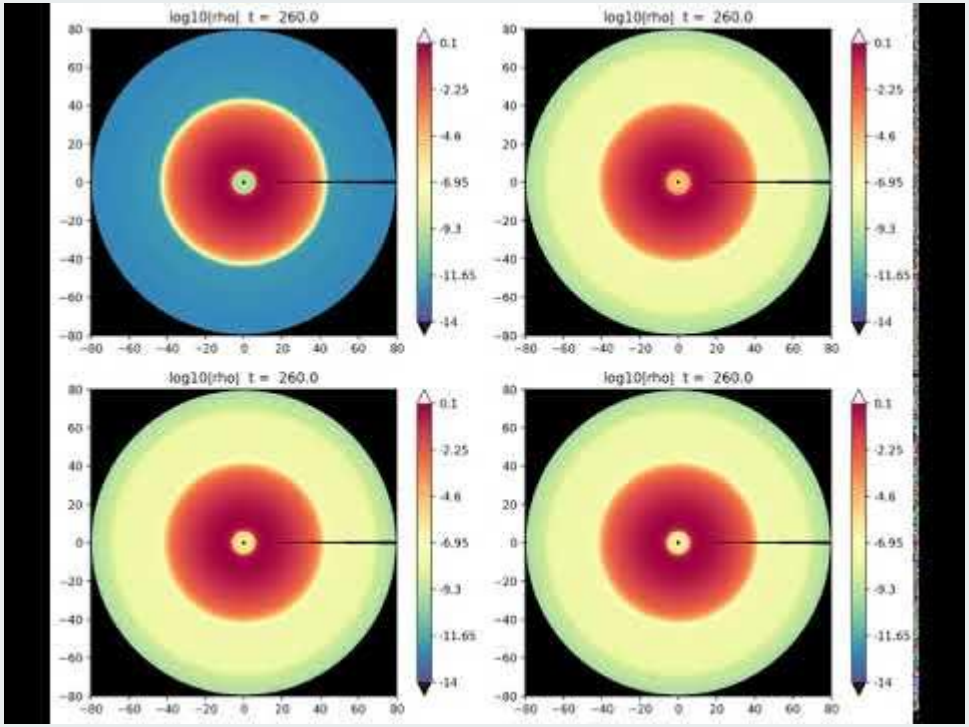
$\Gamma = 4/3$

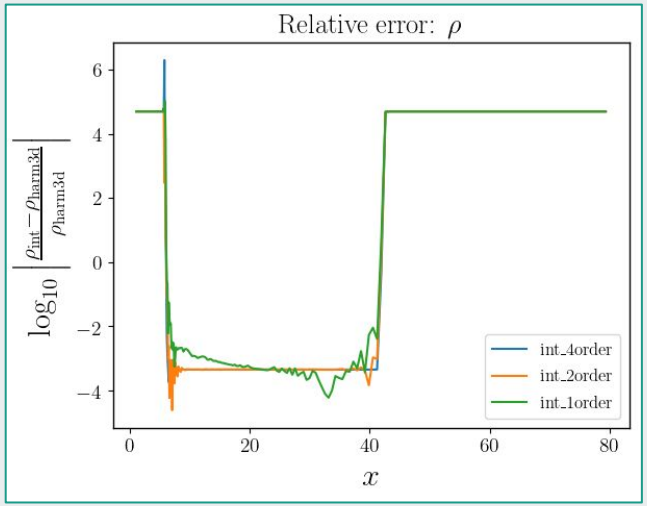


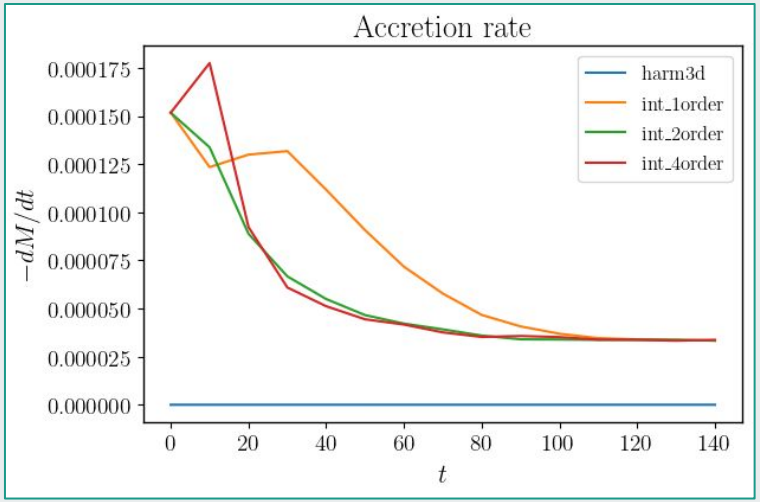
$\Gamma = 2$



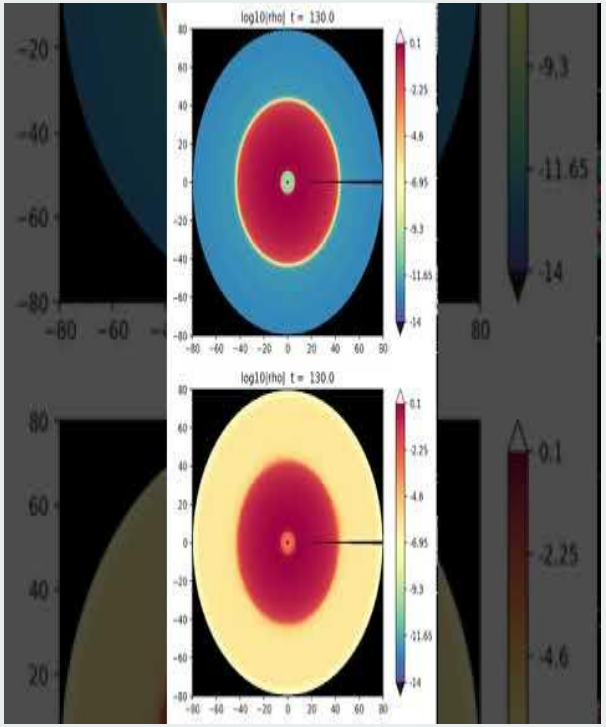
Hand-Off: FM (Γ = 4/3)

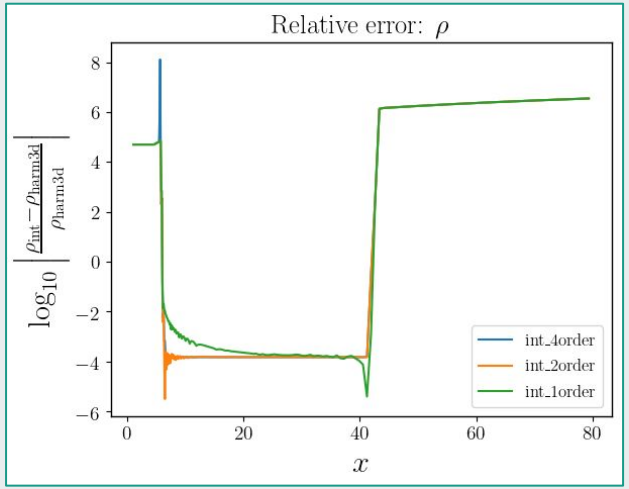


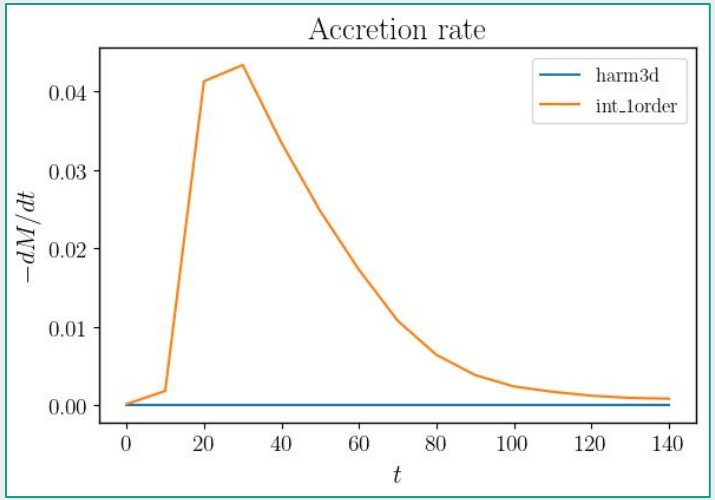


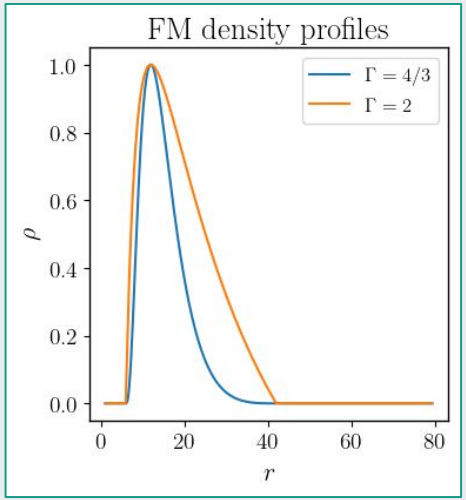


Hand-Off: FM (Γ = 2)









Hand-Off:
BNS post-merger
(work in progress)

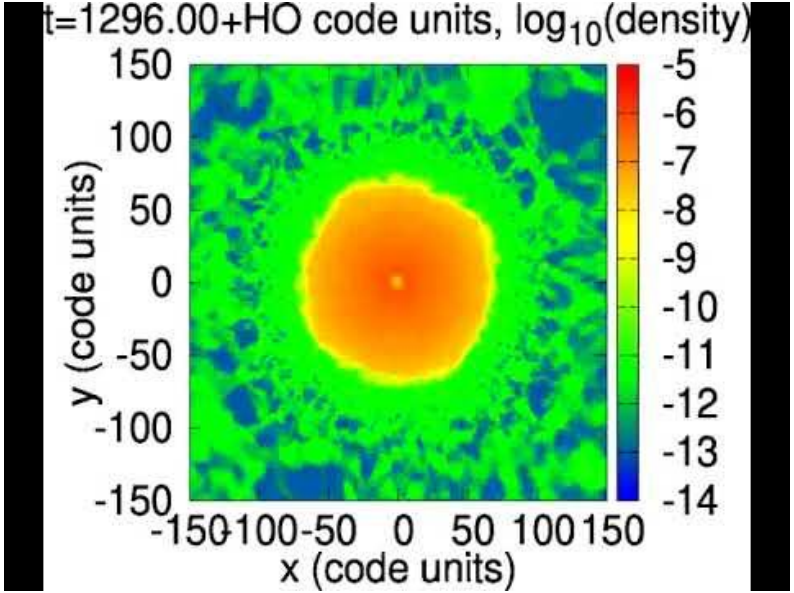
Hand-Off: BNS post-merger

1. Evolve with IGM an equal-mass BNS merger, just-hydro, with Γ-law EoS (Γ=2), until stationary spacetime.

2. Handoff hydro and geometric functions.

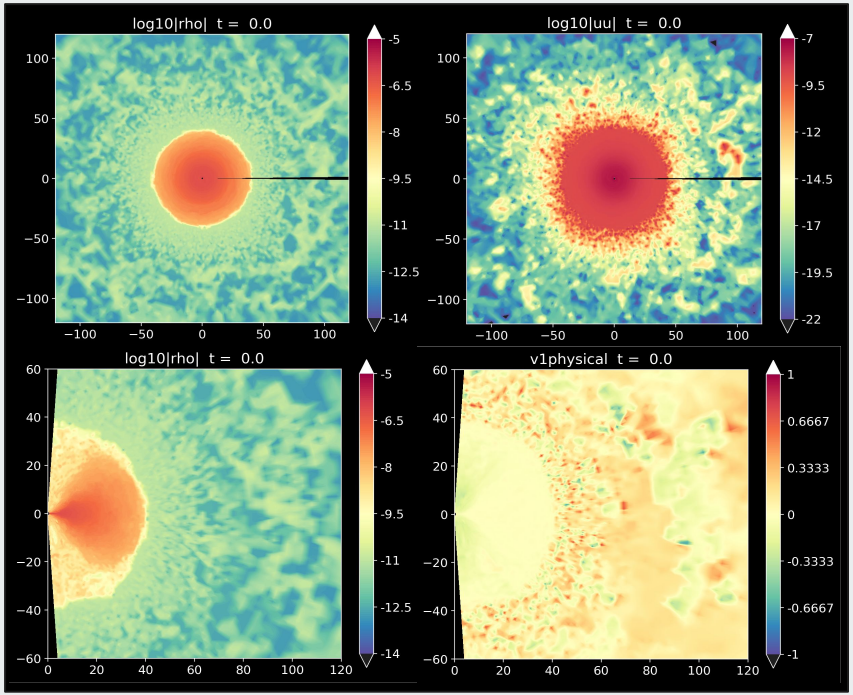
3. Extra step: boost coordinate system to final BH frame.
   BH properties: $M_{\rm Irr} = 2.592, \chi_{\rm BH} = 0.8069$

4. Evolve BNS post-merger in `HARM3D`.

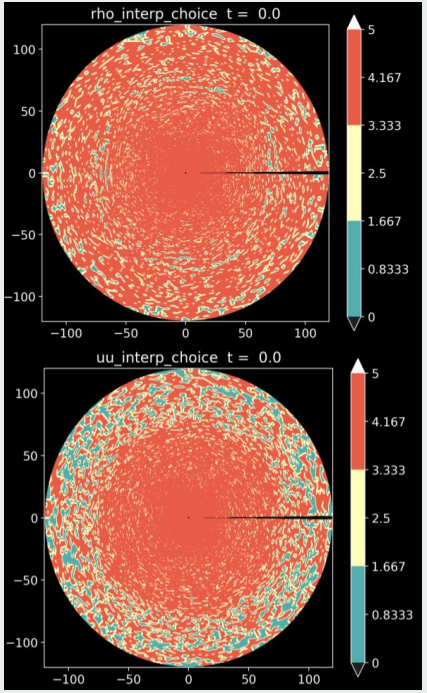


Hand-Off: BNS post-merger

Handed off snapshot

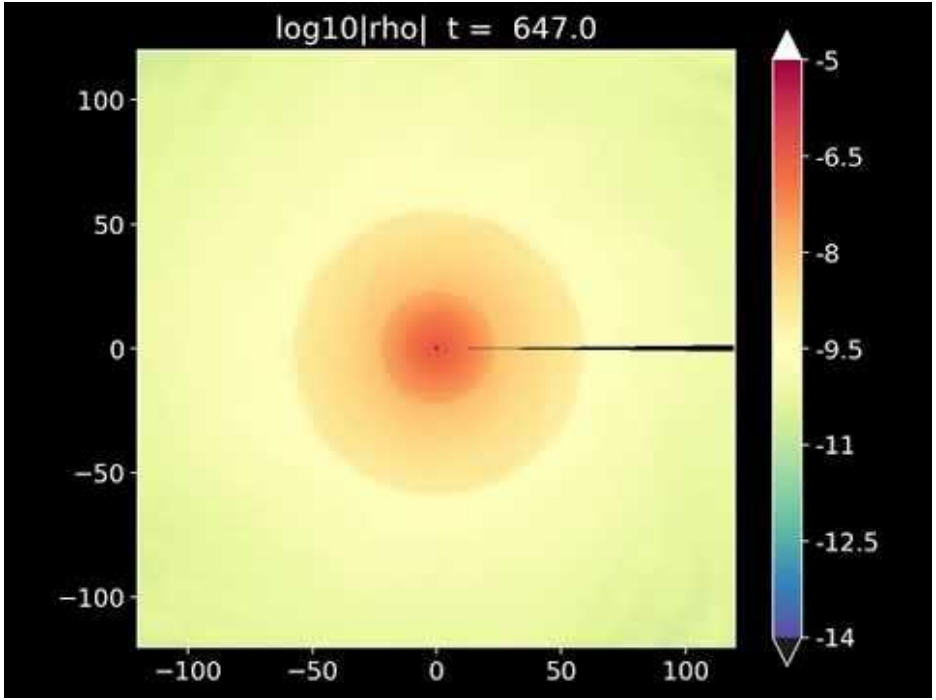


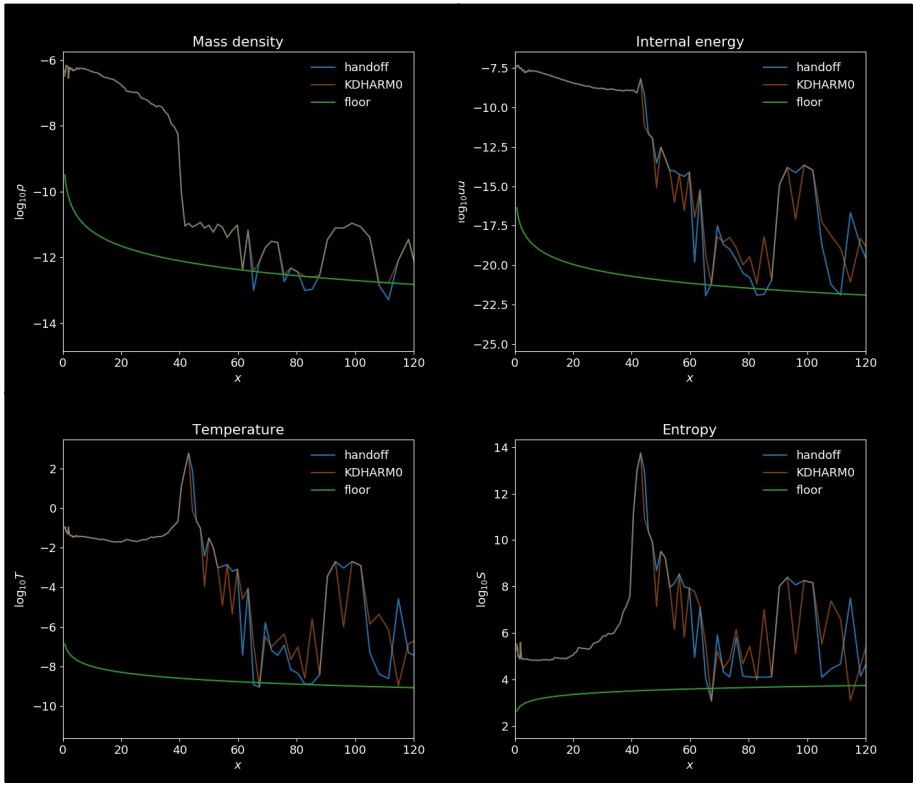
Selective interpolation orders



Results: BNS post-merger

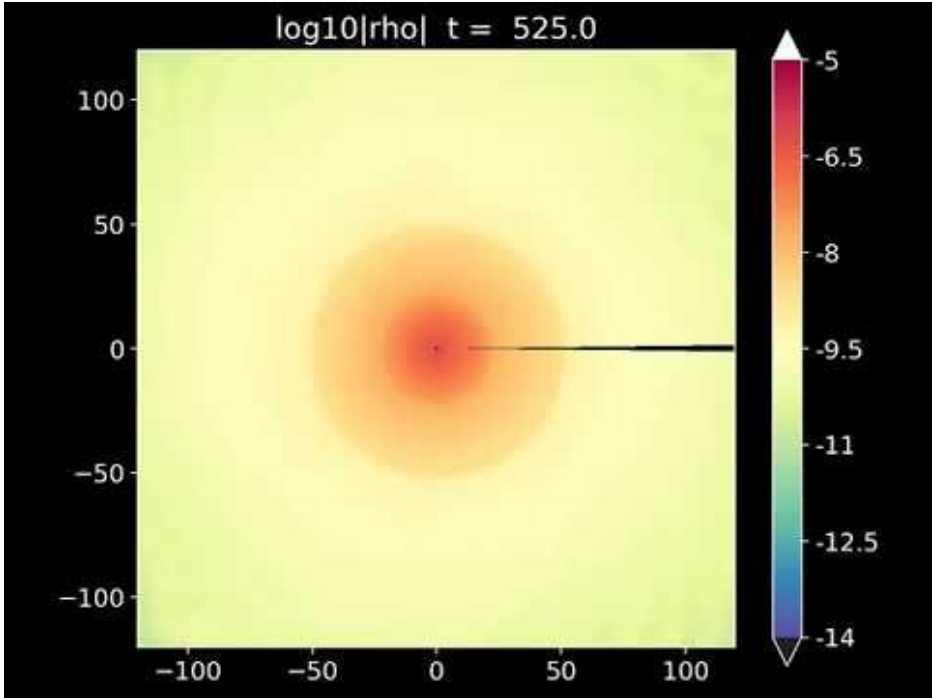
Test0: Original dataset

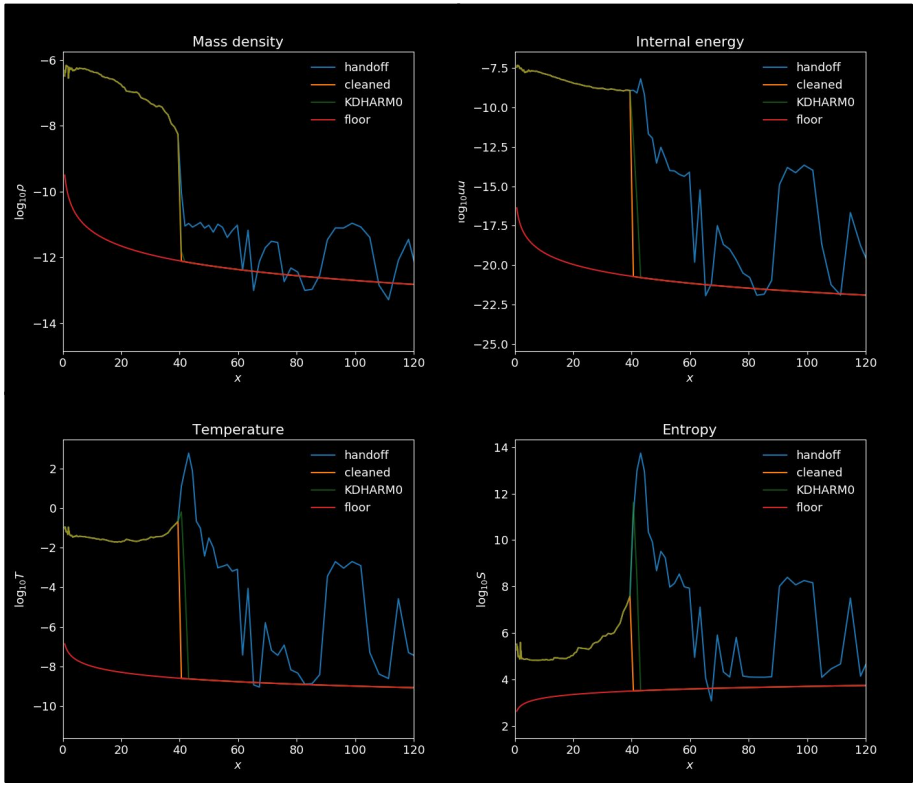




Results: BNS post-merger

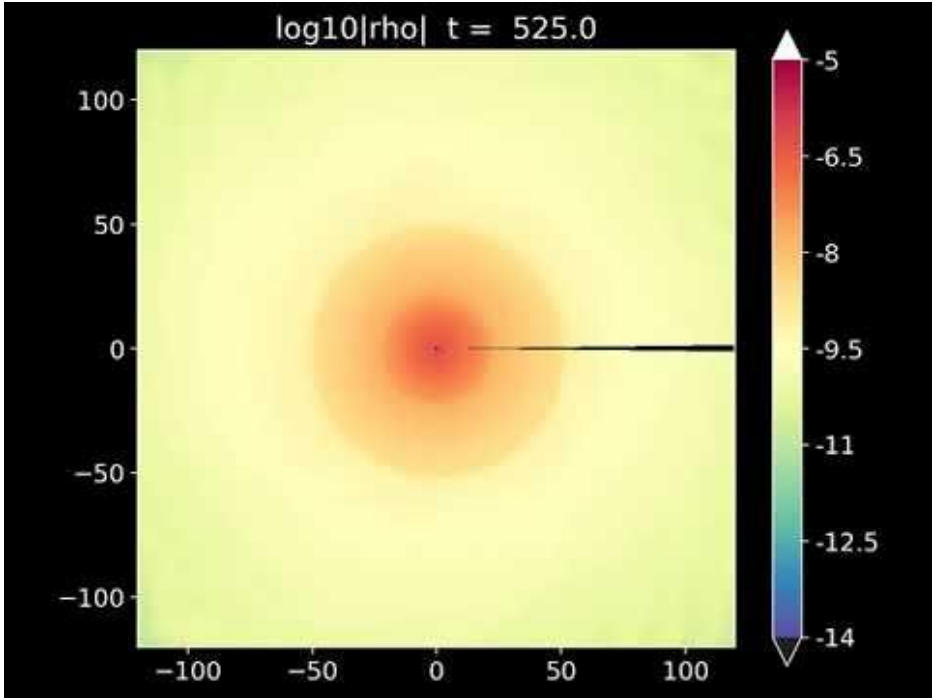
Test1: Cleaning to cool floor

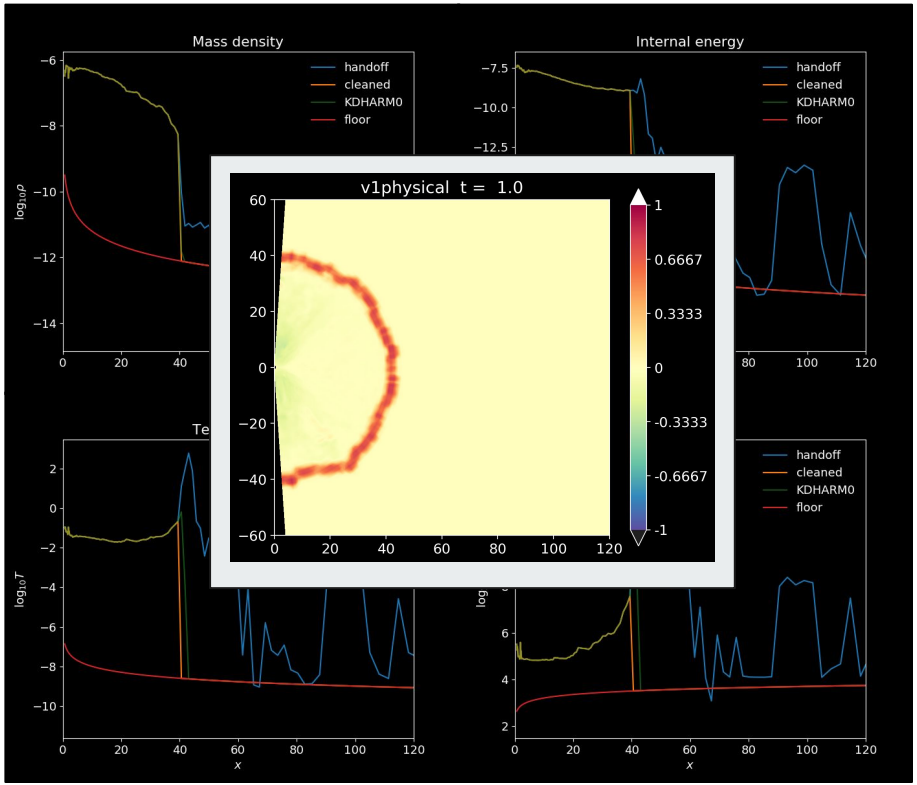




Results: BNS post-merger

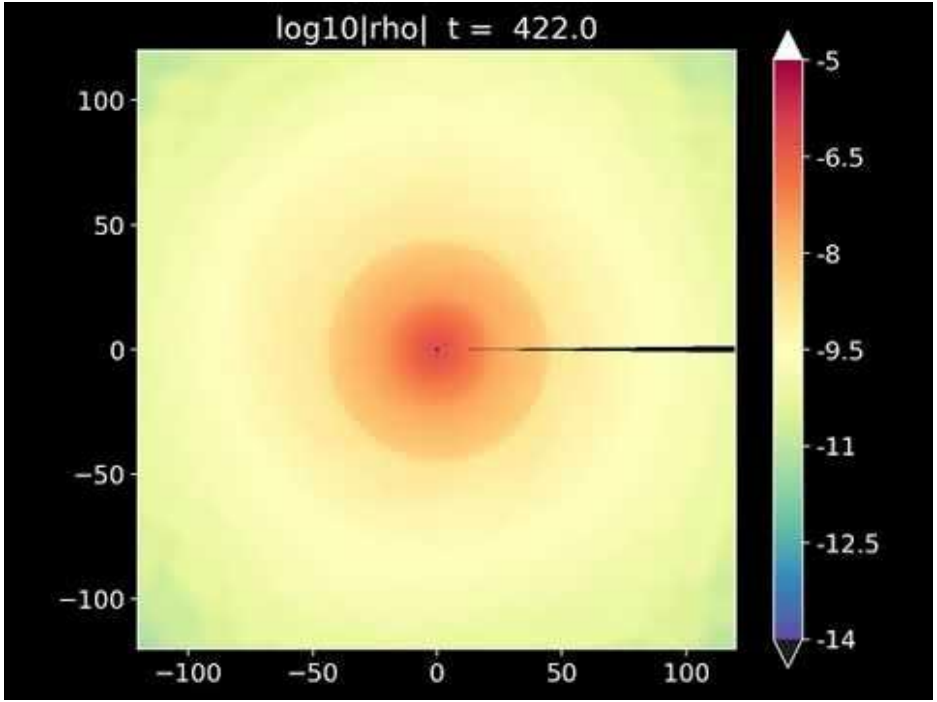
Test1: Cleaning to cool floor

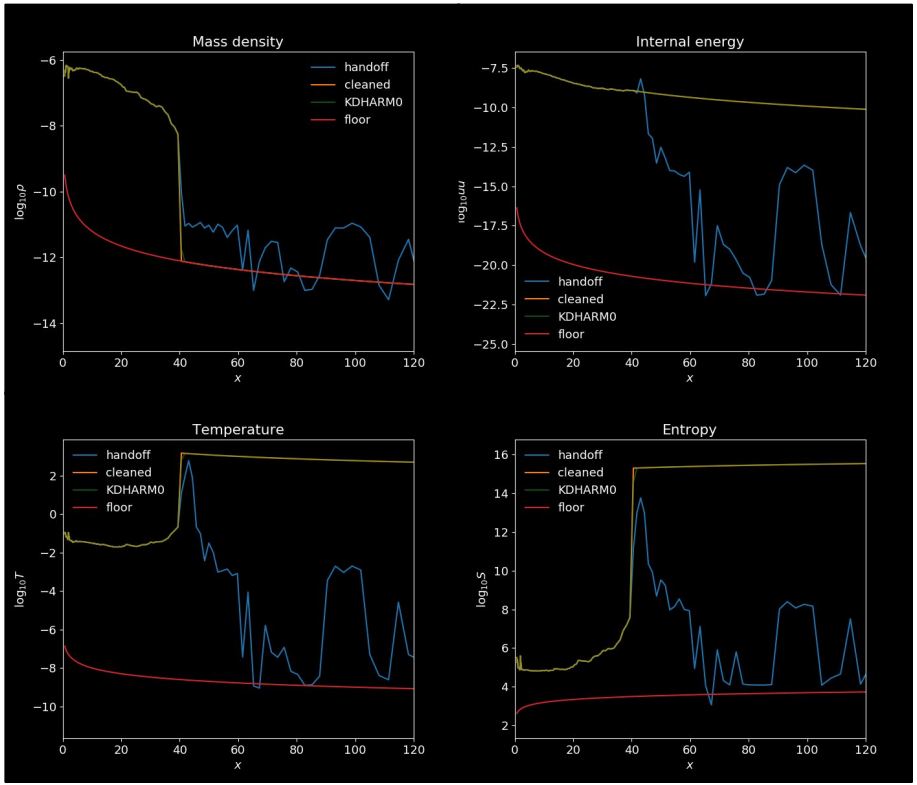




Results: BNS post-merger

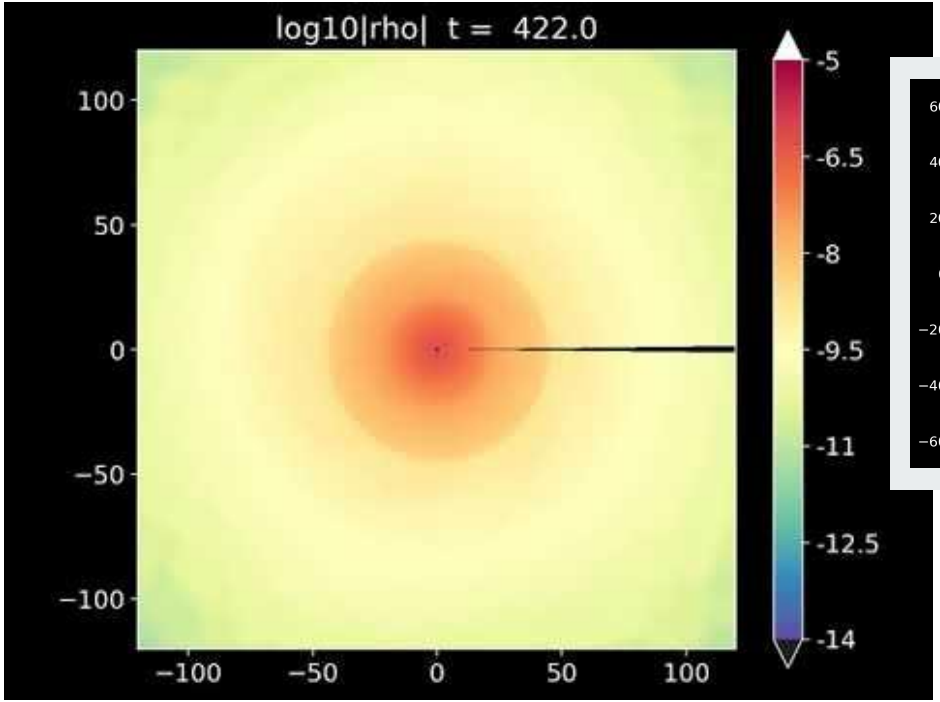
Test2: Cleaning to hot floor

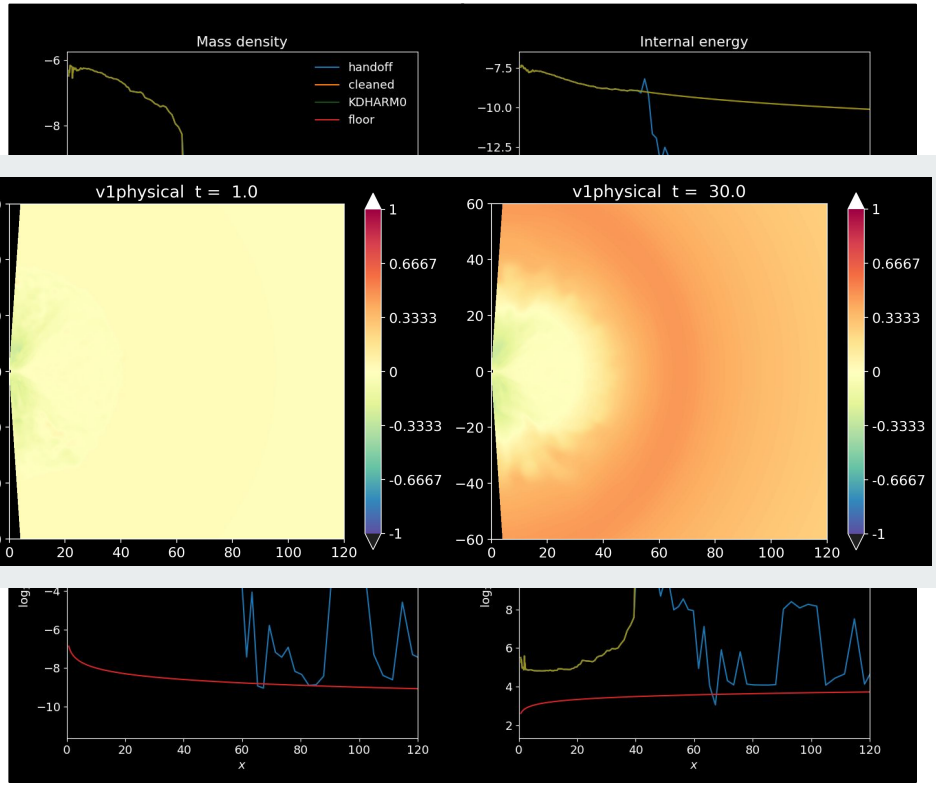




Results: BNS post-merger

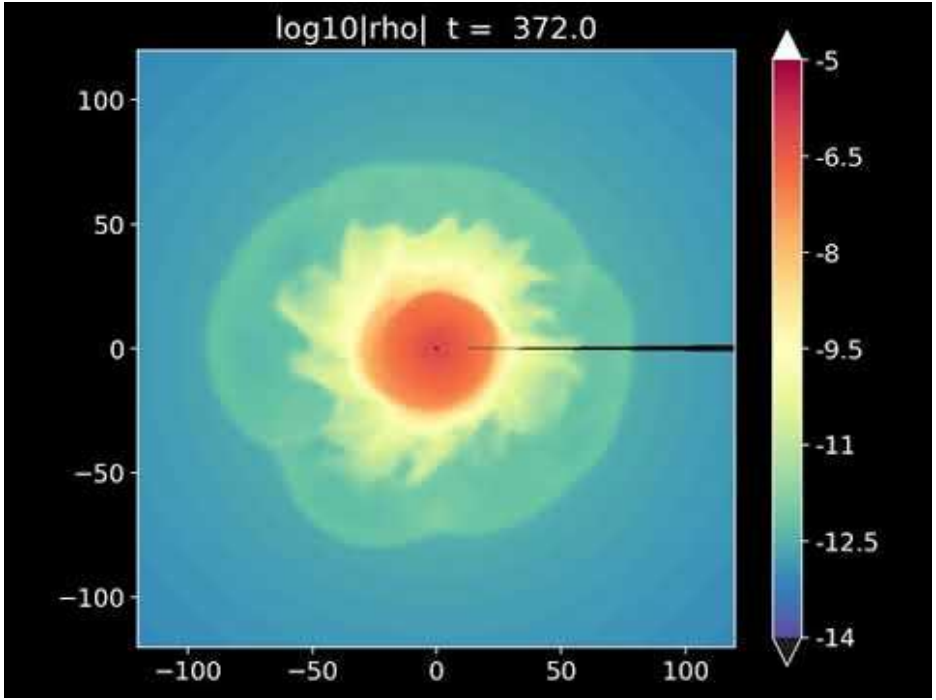
Test2: Cleaning to hot floor

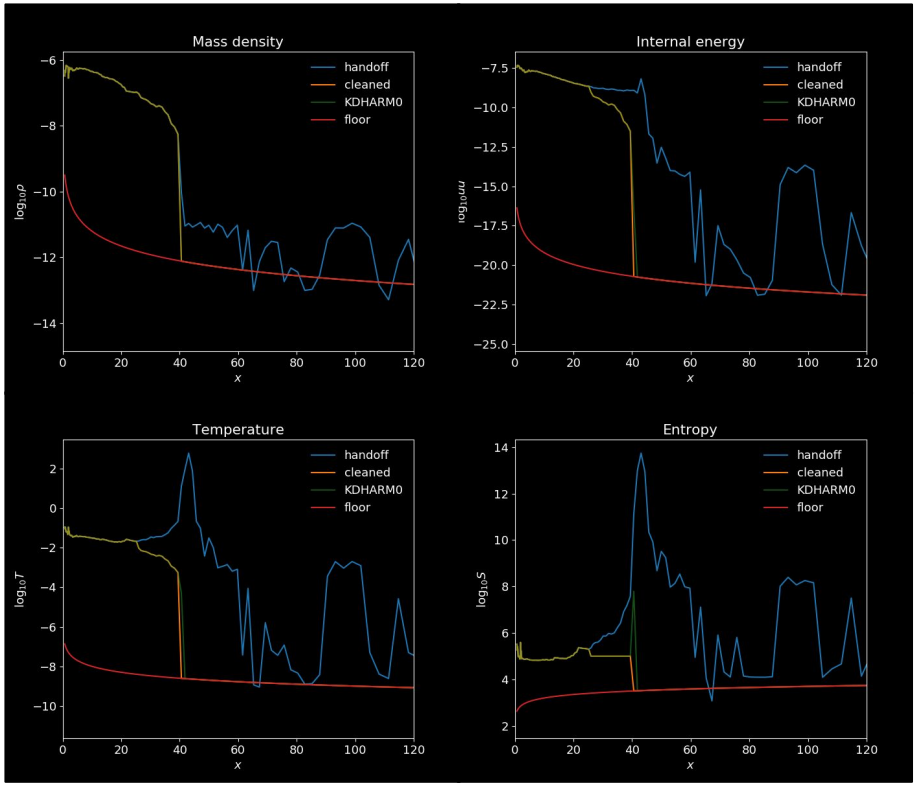




Results: BNS post-merger

Test3: Cooling tail of disk





Results: BNS post-merger

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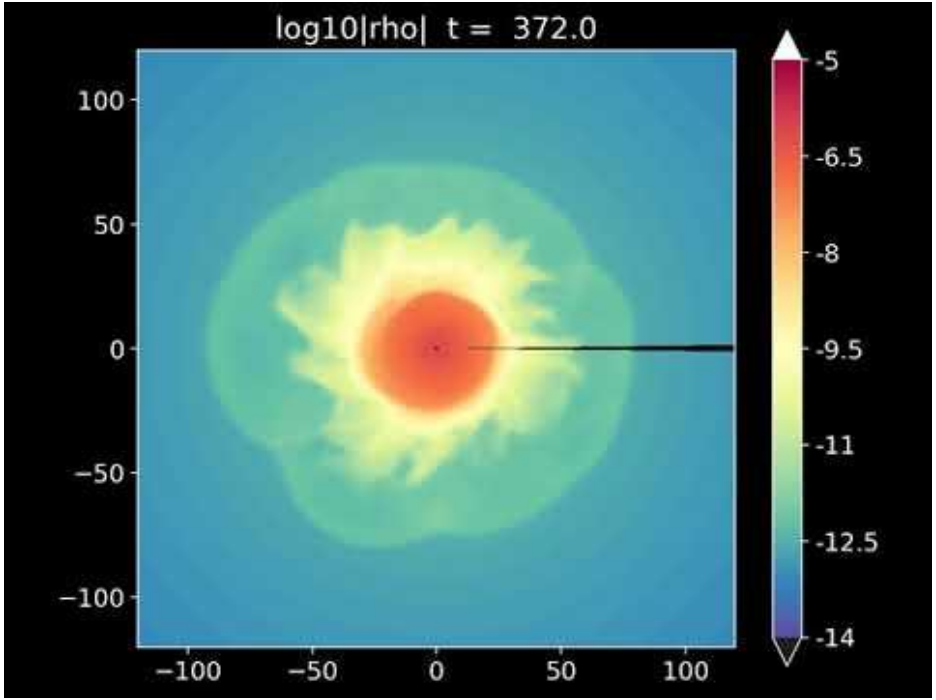
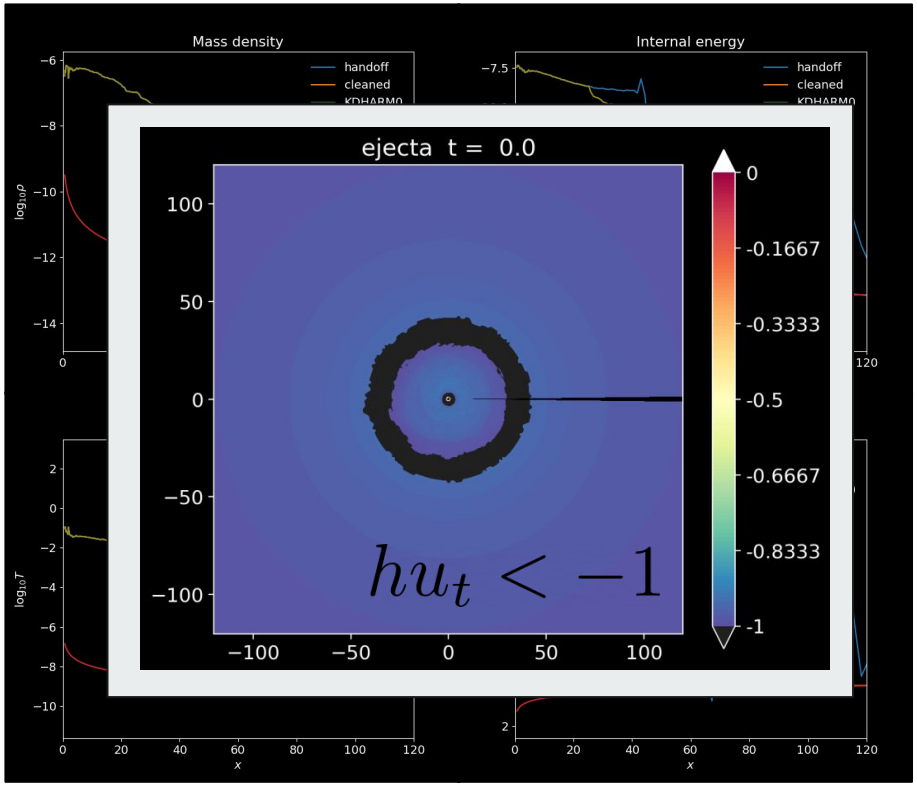
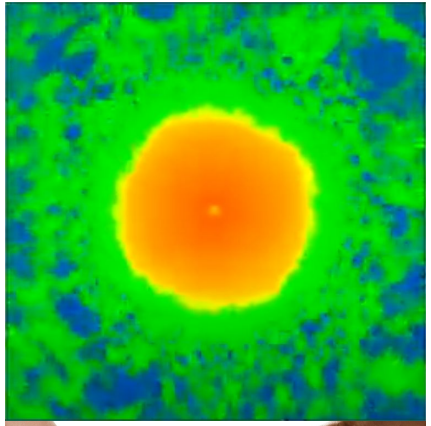
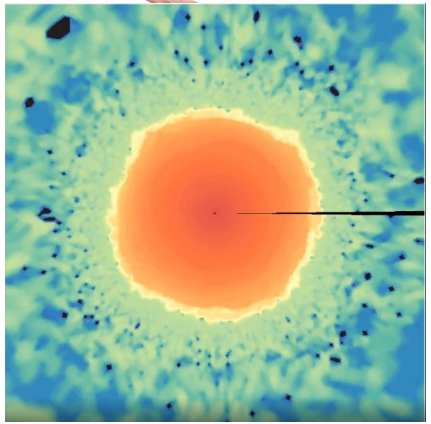




Concluding remarks

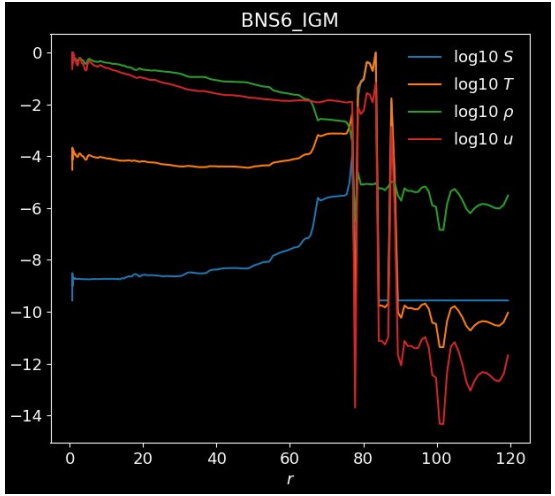
- The Hand-Off package between `IGM` and `HARM3D` proved to work for FM disks.
- BNS post-merger require further care and handing-off techniques.
- Realistic atmosphere? Discriminate bound from unbound material? Effects of ceiling the pressure of the atmosphere?
- TODO:
  - Test and debug restart routines.

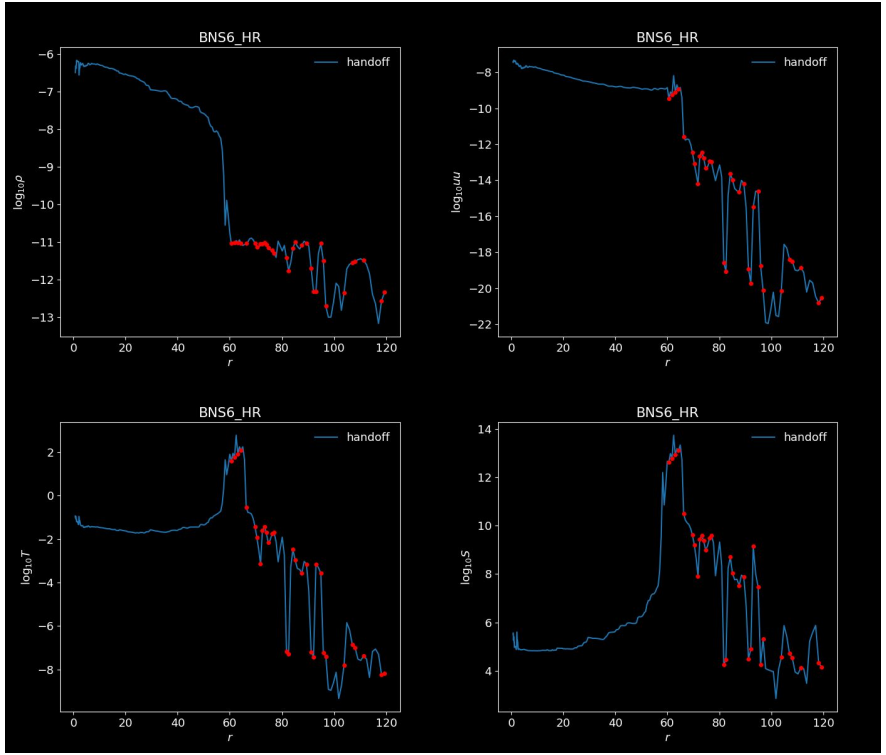




Thank you!

Sanity checks





Sanity checks