GRACE: Numerical Relativity in the GPU Era

Carlo Musolino — 05.02.2026
"*Multi-Messenger Astrophysics in the Dynamic Universe*" Workshop, YITP

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Outline

- Introduction

- The `GRACE` code

- Results

- Conclusions

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Introduction

- GPU computing is the most efficient ``brute force'' available

- Many NR codes are transitioning towards it
  [Shankar+2022,Stone+2024,Kalinani+2024,Fields+2024,Palenzuela+2025]

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The GRACE code

- General Relativistic Astrophysics Code for ``Exascale''

- **Oct-tree based** grid provided by `p4est`

- Backend **parallelism** from `Kokkos`

- **Open source soon!**

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The GRACE code

- `p4est` provides **host-side** grid book-keeping

- Data operations exclusively on device

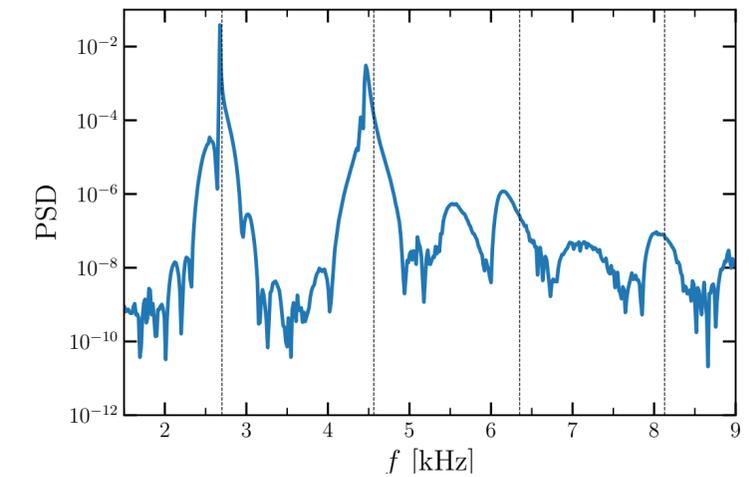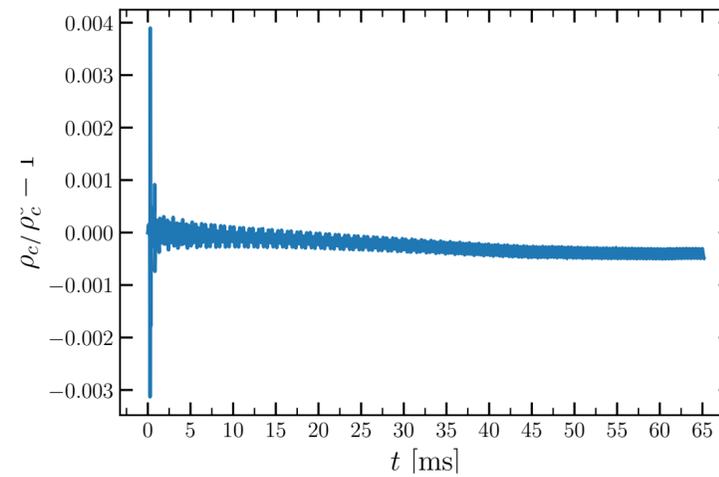- Ghost-zone exchange and boundary conditions via **custom task-based** system

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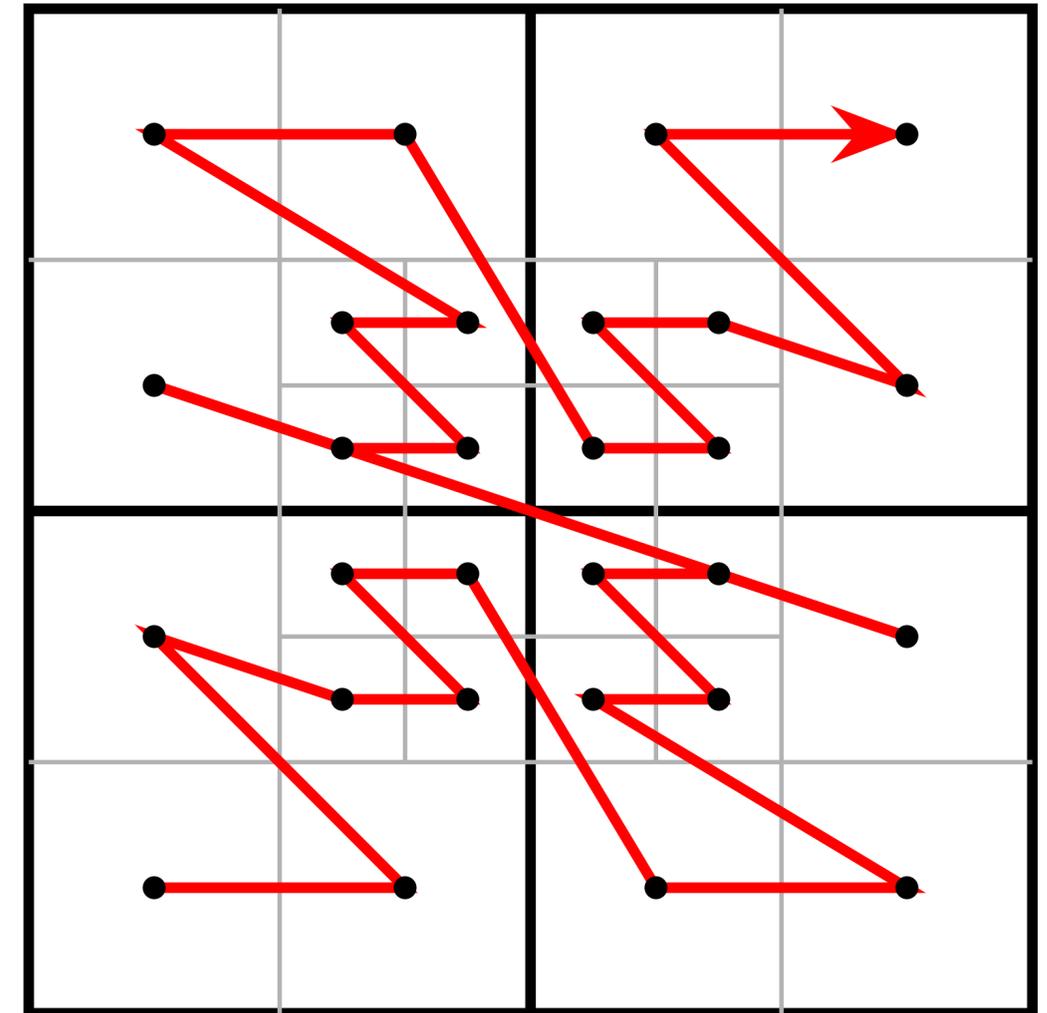
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Results — GRMHD

- Hydro: HLLE Riemann solver + WENO-Z + positivity-preserving limiter

- GRMHD module based on ``Upwind CT scheme" of [Del Zanna+2007, Mignone+2020]

- Refluxing + EMF recirculation at mesh refinement boundaries

Magnetized rotor test

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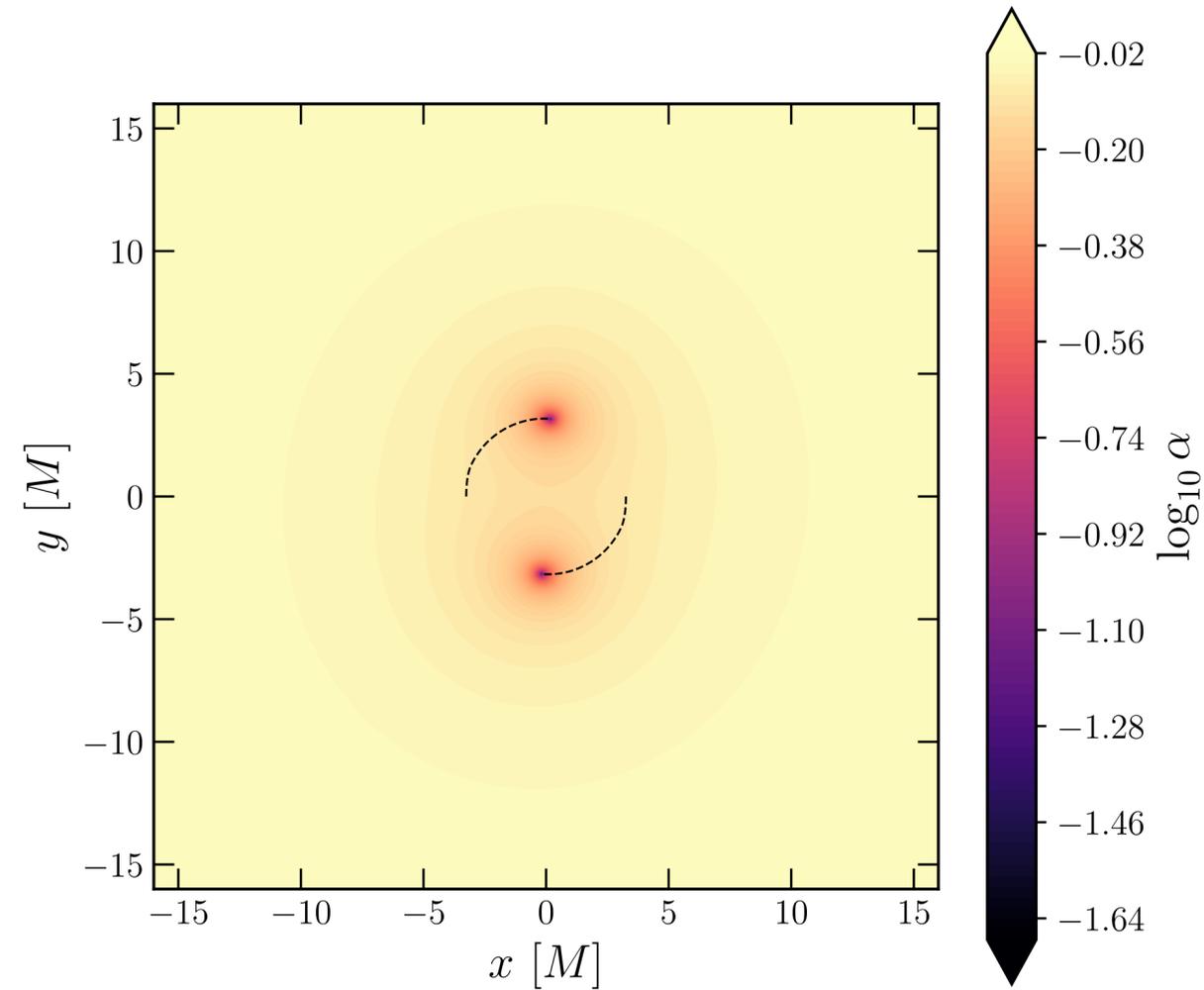(Albert Einstein Institute)
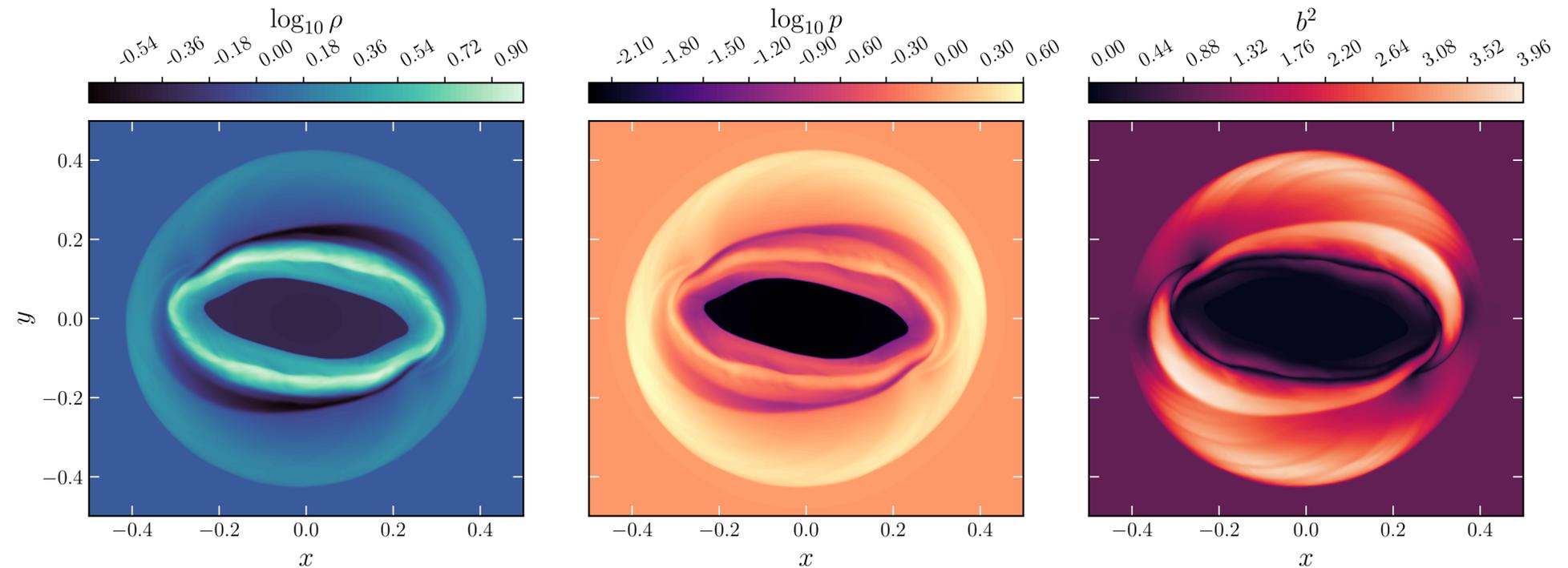
Results — Z4c

- Spacetime evolved according to conformal Z4 formulation [Hilditch+2013]

- 1+log slicing and Gamma driver shift condition

- Discretized with 6th order finite differencing
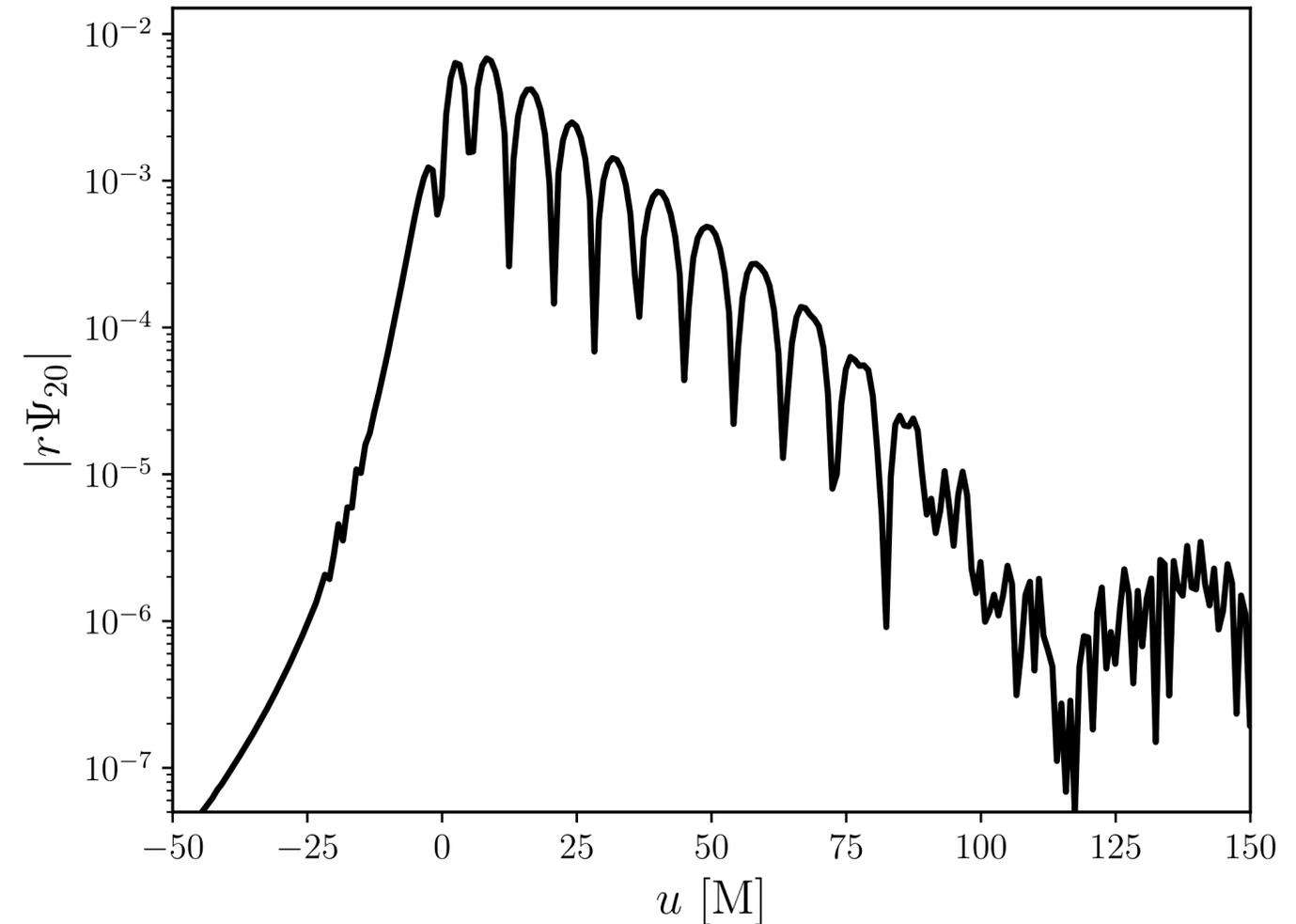
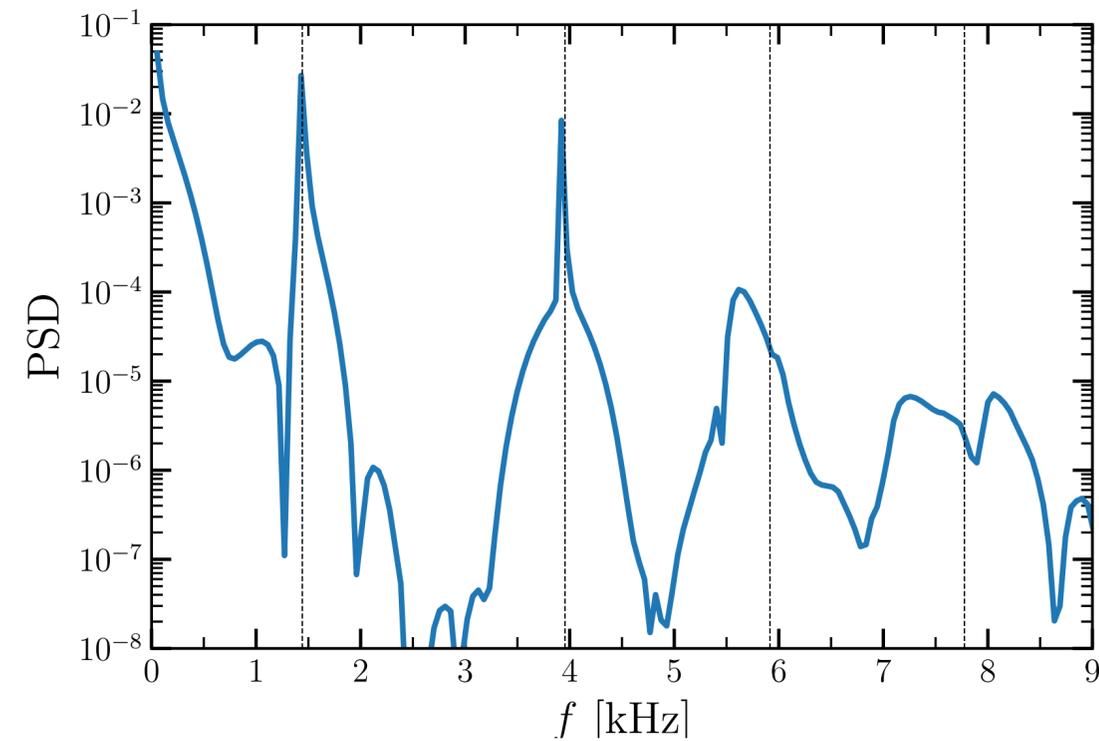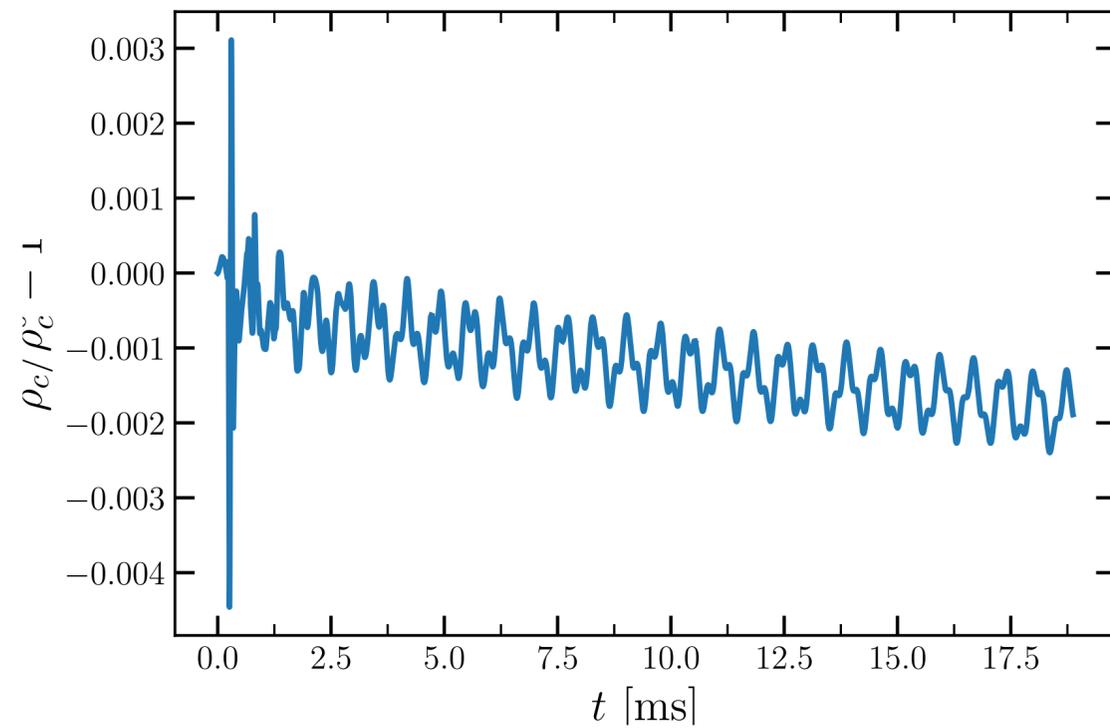Perturbed spinning puncture, see also [Zhu+2024]

Results — Z4c

Binary puncture evolution, same setup as [Brügmann+2008,Daszuta+2021,Zhu+2024]
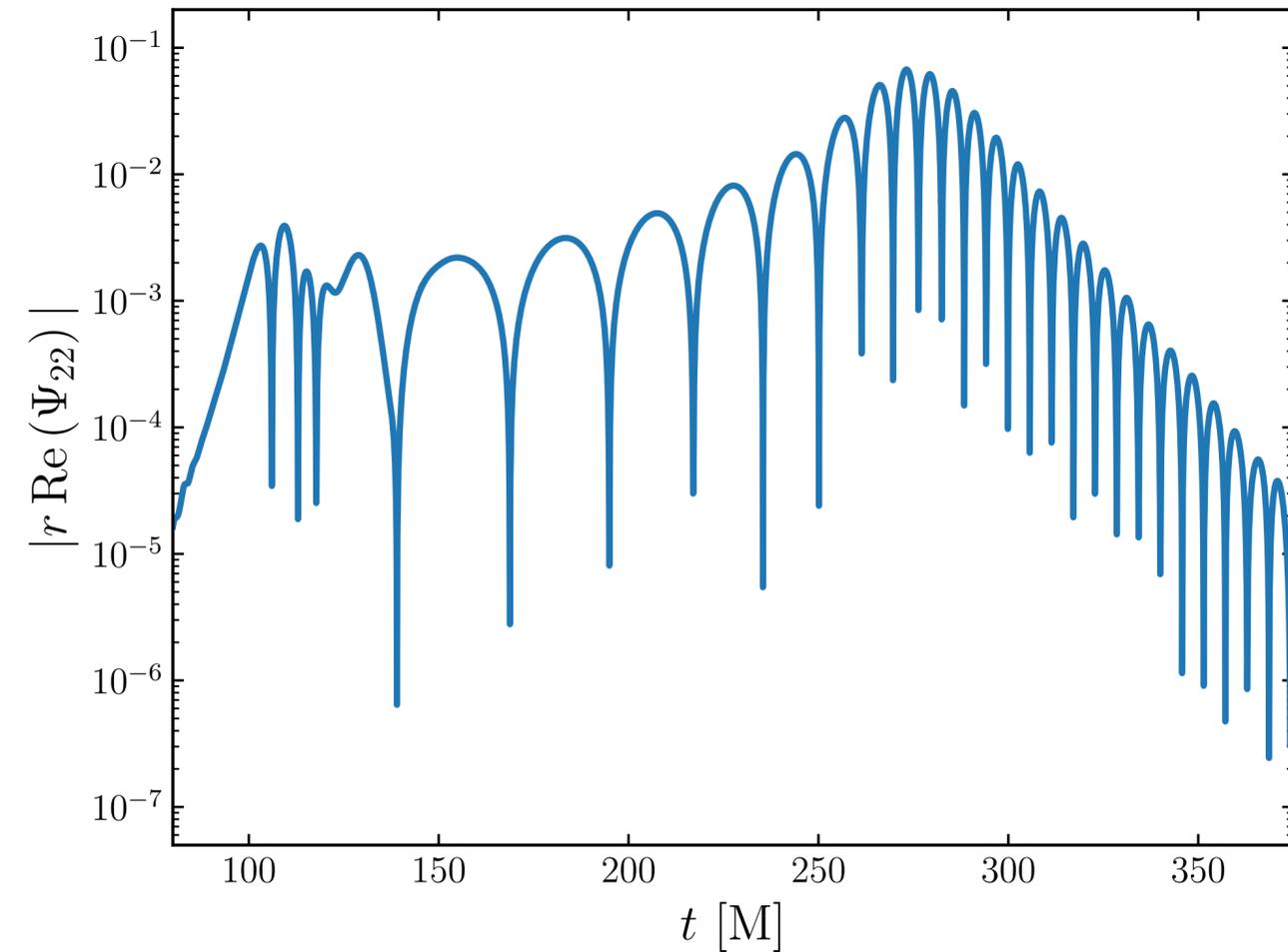
Results — Z4c + Hydro
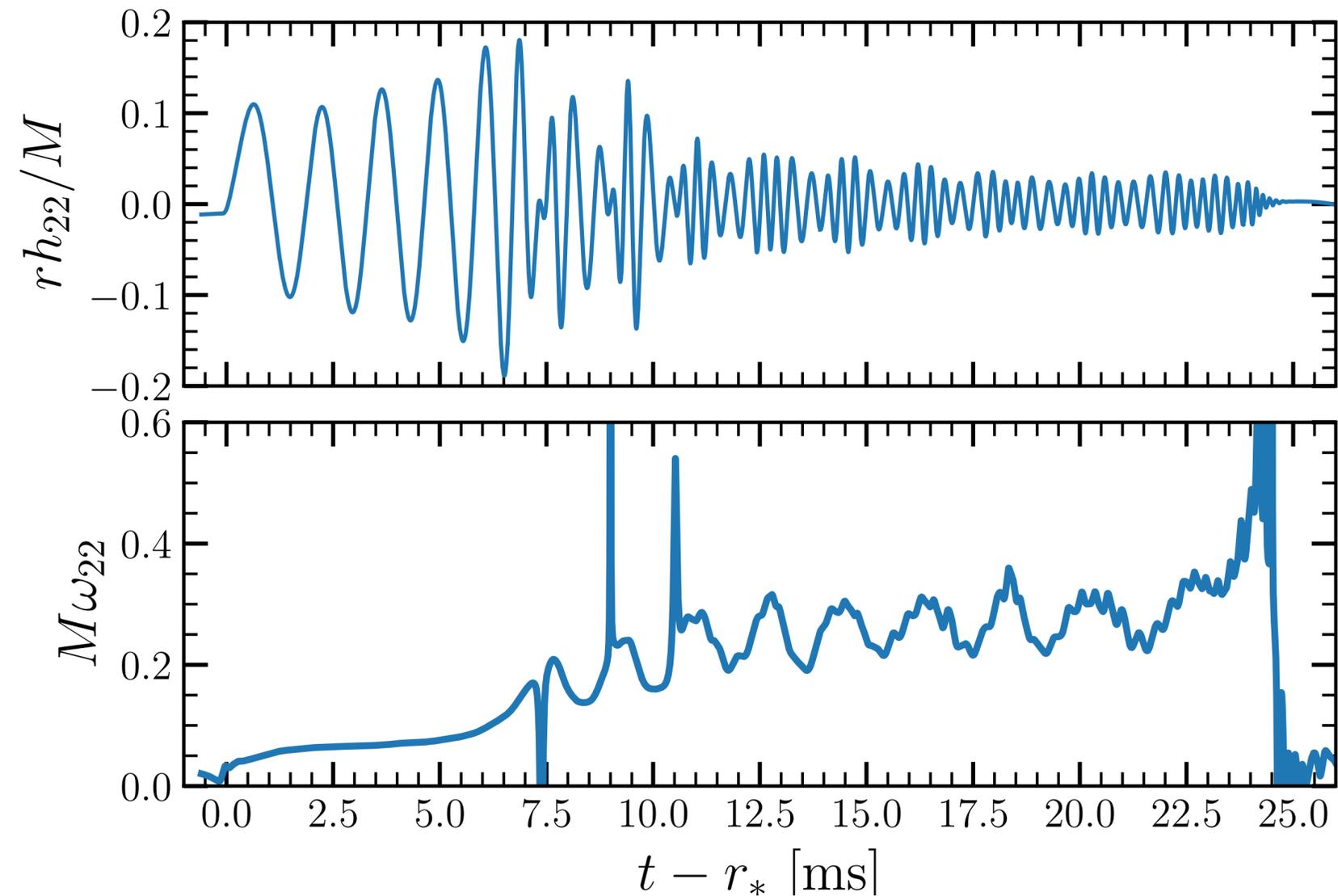
TOV pulsations with dynamical spacetime

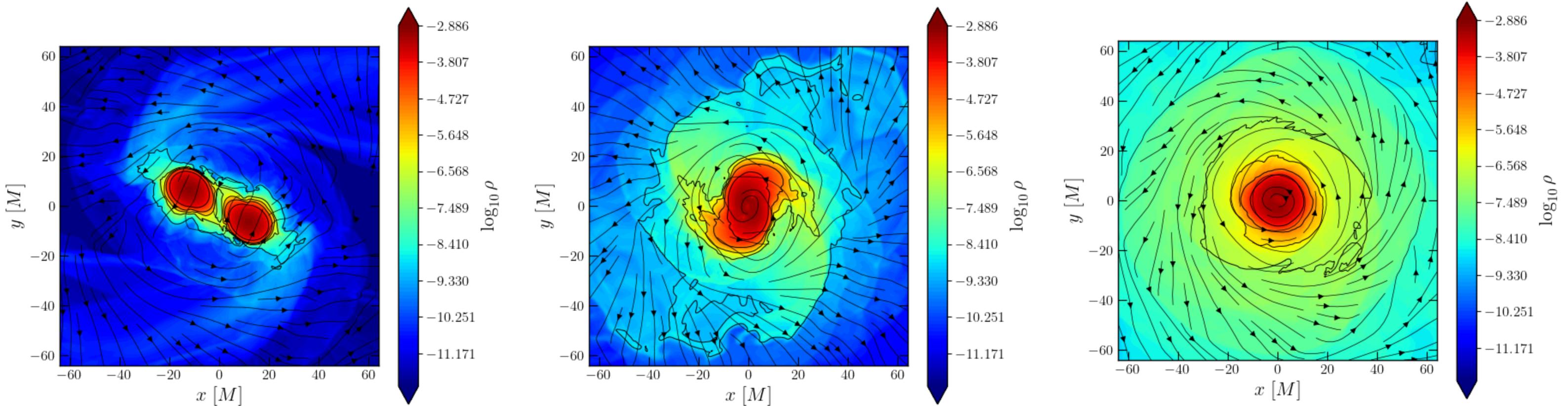**MAX PLANCK INSTITUTE**
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Results — BNS merger

Binary neutron star evolution, initial data from LORENE with $M_{\mathrm{ADM}} \simeq 3$ with $\Gamma = 2$ polytrope

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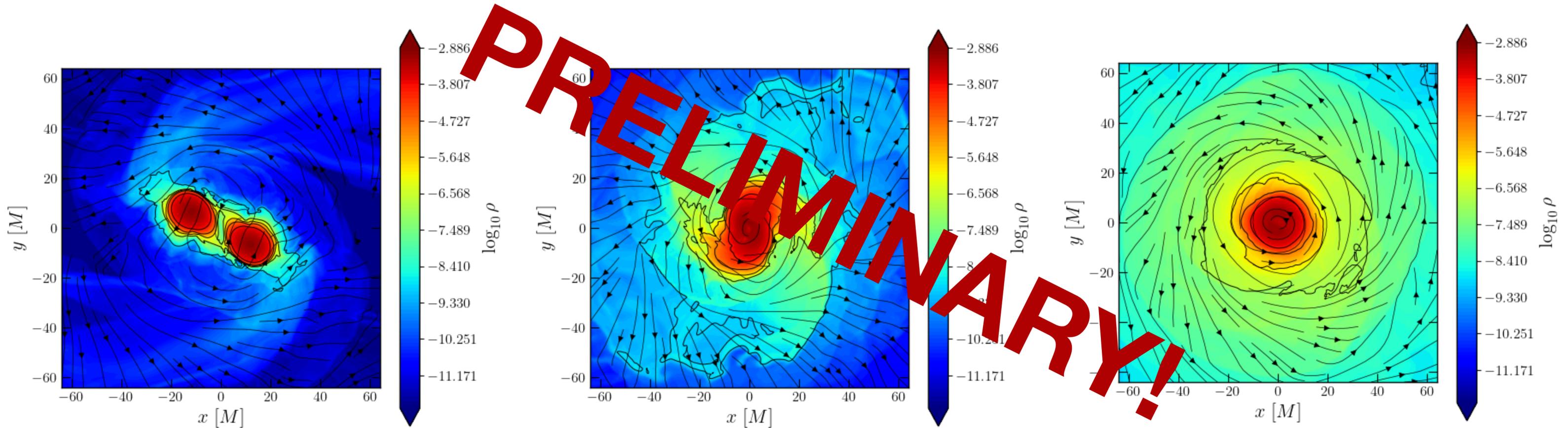(Albert Einstein Institute)

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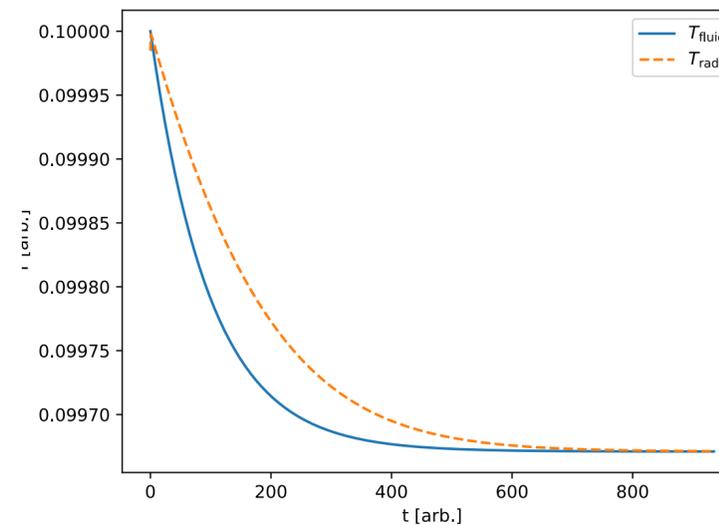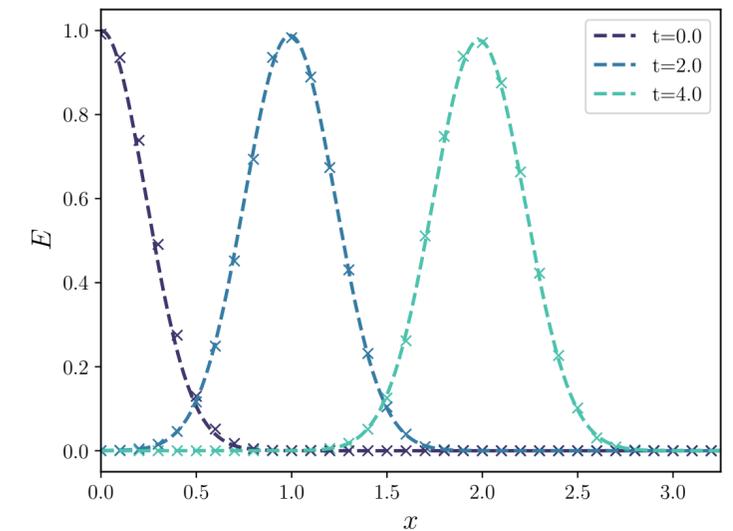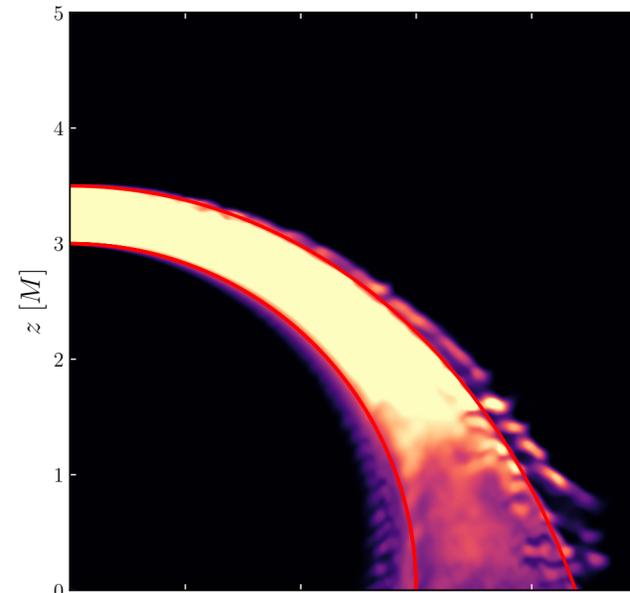
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Results — Radiative transport

- Gray M1 radiative transport

- ``Workhorse'' transport scheme, widely used in NR [Foucart+2015,Radice+2022, many more]
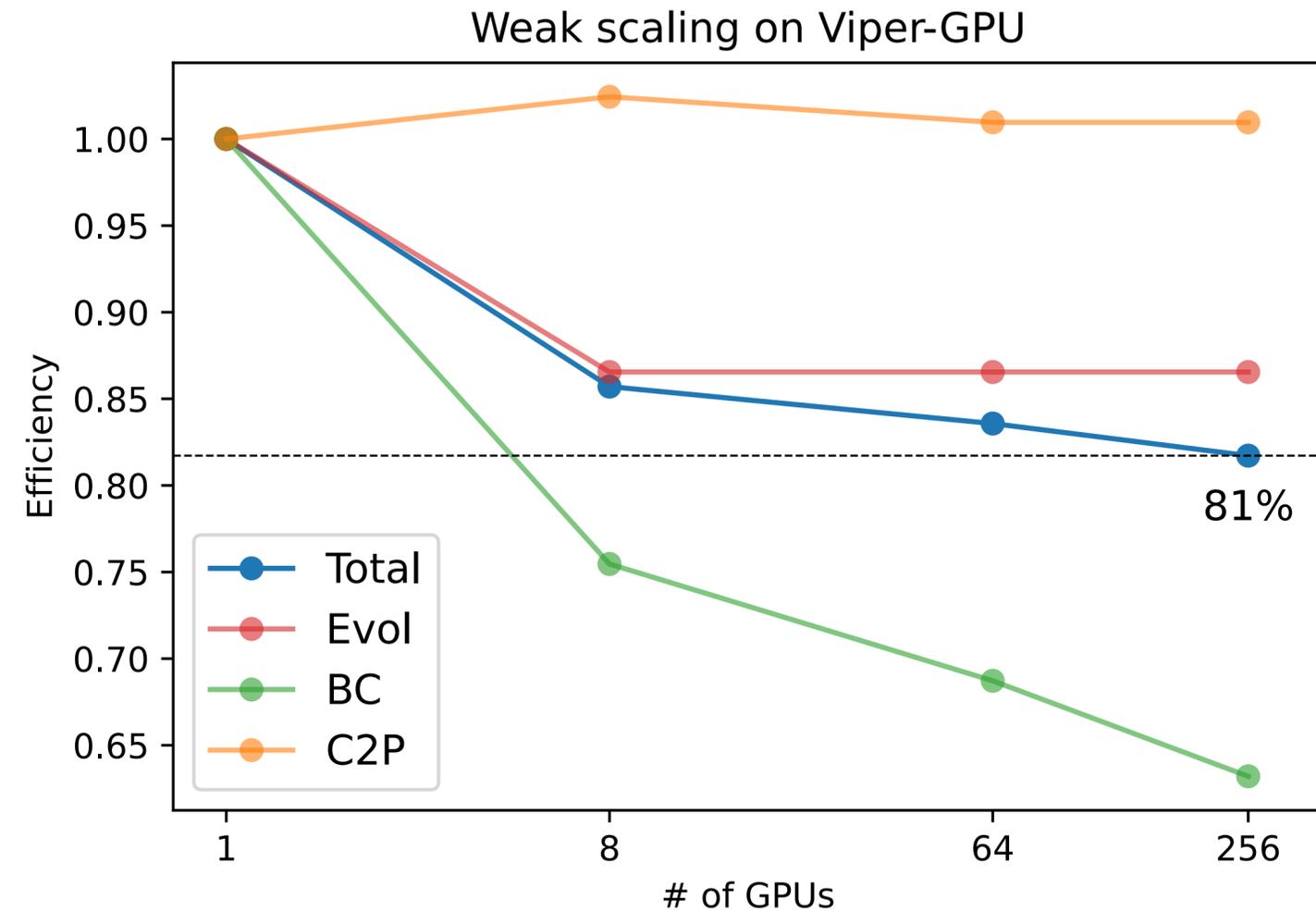
- Microphysics on the way
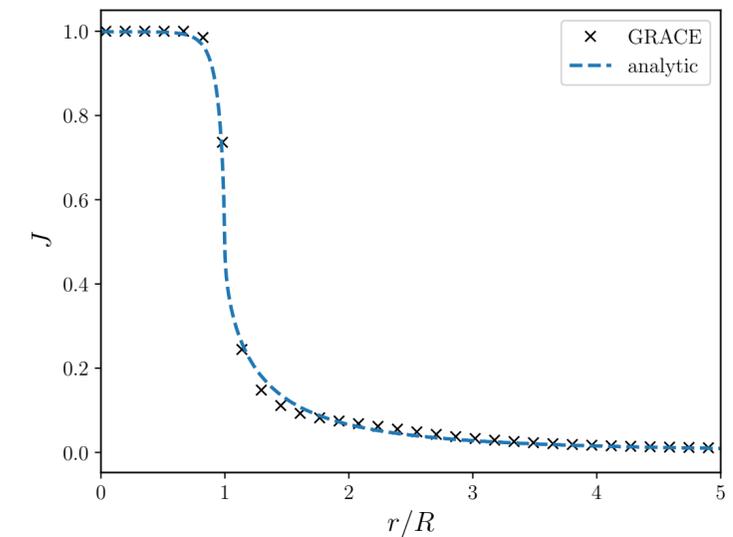
Results — Performance

	GRMHD	Z4c	GRMHD+Z4c
Mi300A	24.6	10.9	8.67

Code performance in 10^6 ZC/s on a single card, 64 blocks of 64^3 cells + ghostzones

Measured on Viper GPU @ MPCDF

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Results — Performance

Code scaling on Viper GPU @ MPCDF

Conclusions

- GPU-enabled NR code may soon be a necessity

- Presented a new GPU code framework

- Currently under testing, open source soon

- Accurate microphysics and radiative transport under development