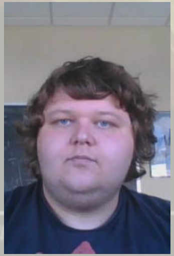
Numerical Relativity Simulations of Compact Binary Mergers

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5th August
2024 Frontera User Meeting





On behalf of the Numerical Relativity group: D. Radice, M. Bhattacharyya, P. Hammond, J. Fields, A. Rashti, R. Gamba, E. Shukla, P. Espino, T. Pitik, R. Kashyap, Y. Qiu, H. Bandyopadhyay, K. Murase

igc




PennState
Eberly College of Science

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

Numerical Relativity Simulations of Compact Binary Mergers

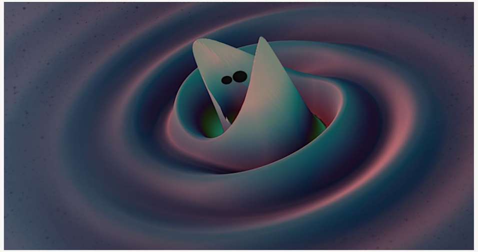
Project: PHY23001 (2023-)

We perform large-scale simulations of BBH and BNS mergers.

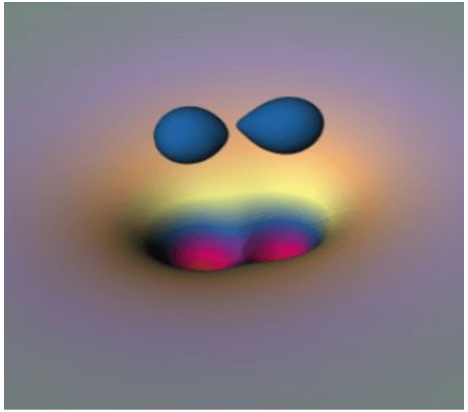
BBH: Main objective is to generate some of the first catalogs of GW waveforms meeting accuracy requirements for next-gen experiments such as LISA, the ET, and CE.

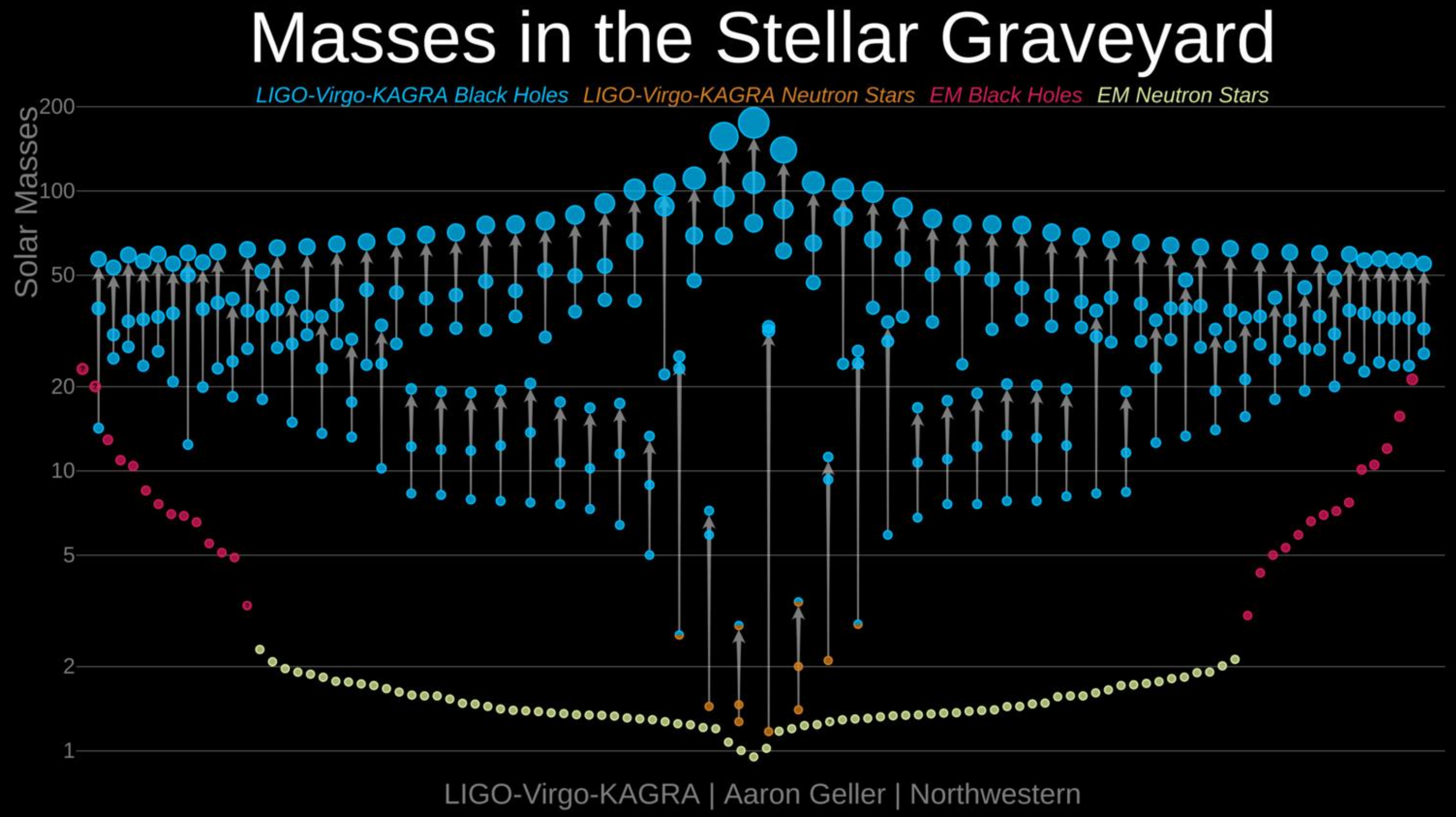
BNS: Explore the impact of magnetic fields and microphysics by performing very high-resolution NS simulations.

Rotating star collapse: Study the MRI in differentially rotating hypermassive neutron-stars



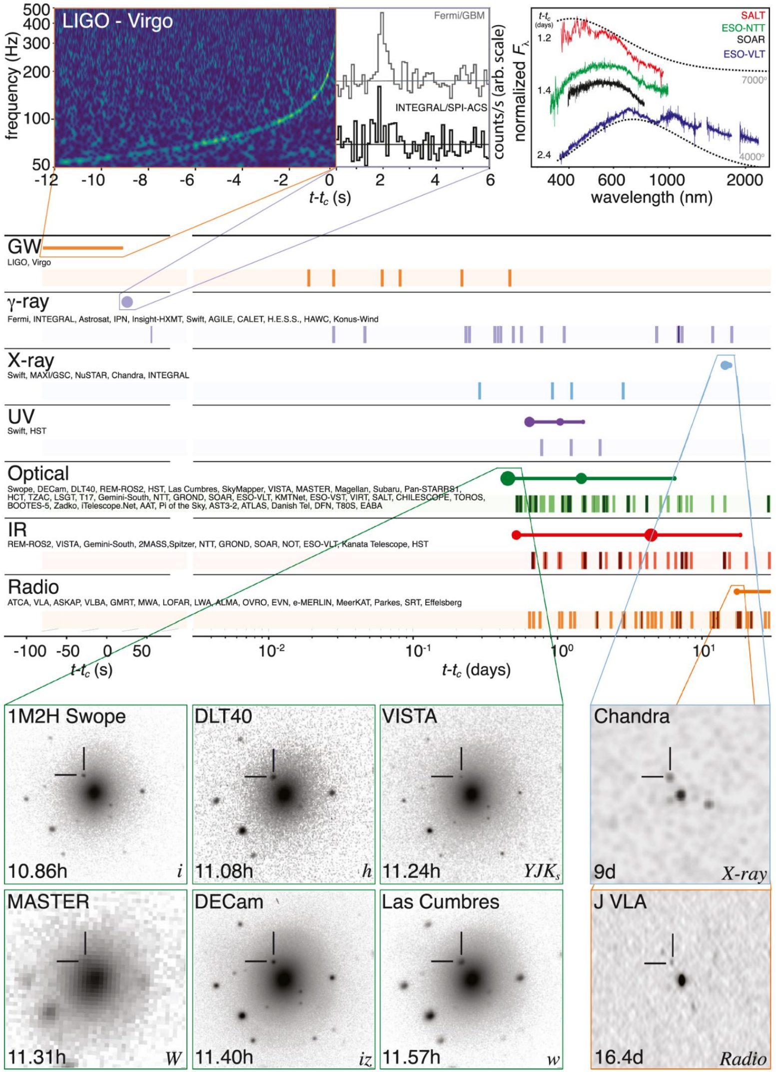
Ripples in the spacetime around a merging binary black-hole system from a numerical relativity simulation. Image credit: Deborah Ferguson, Karan Jani, Deirdre Shoemaker, Pablo Laguna, Georgia Tech, MAYA Collaboration.

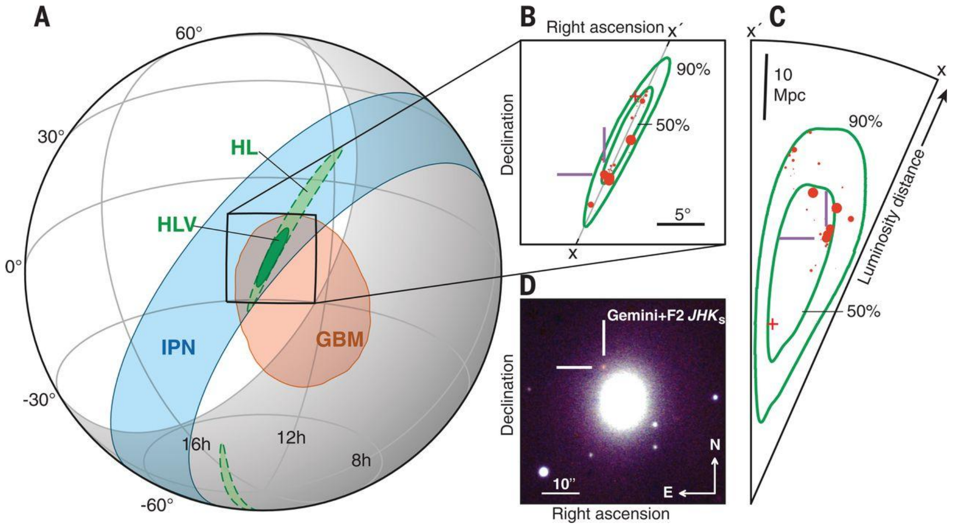




Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817: First multimessenger event of GWs and EM radiation



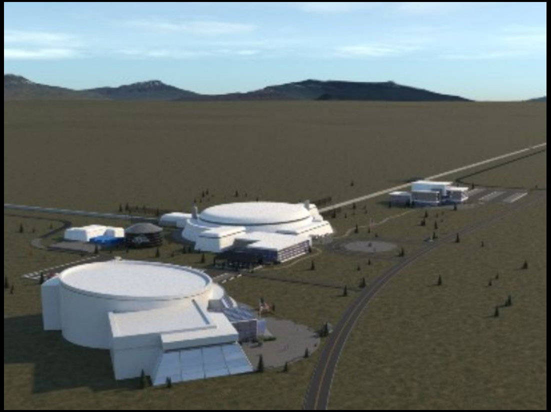


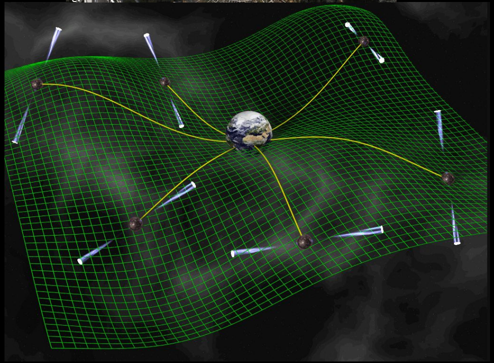
Abbott+ (2017)

An extraordinary era of Gravitational Wave Astronomy is coming!

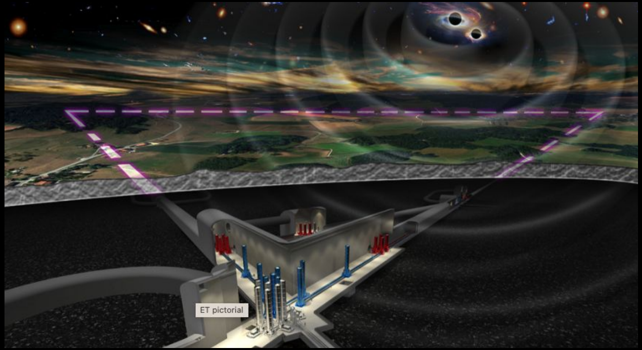
LIGO/Virgo/Kagra

Cosmic explorer





PTAs



Einstein Telescope

LISA

GW astronomy requires accurate waveform models, informed by **Numerical Relativity** simulations. As GW detectors reach higher sensitivity there is a need for even more accurate NR gravitational waveforms of BNS mergers.

That is

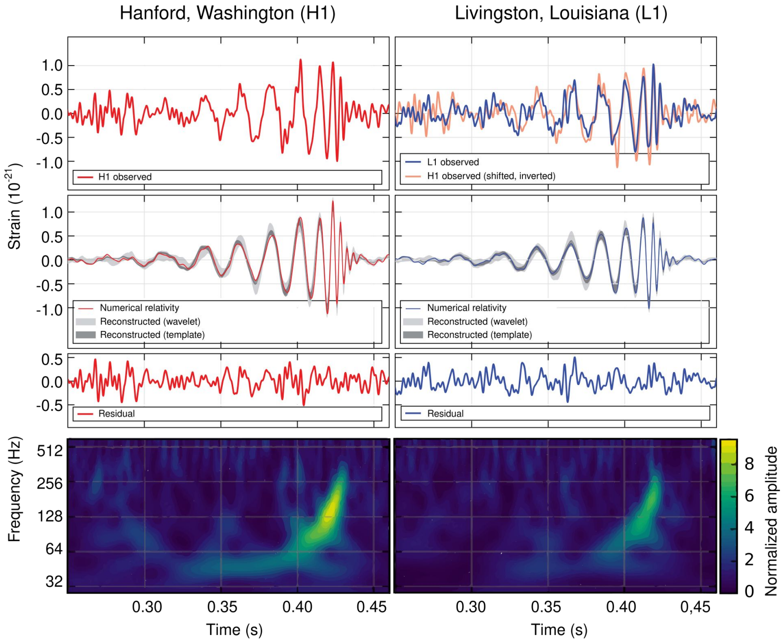
- solving the **Einstein equations** to evolve a dynamical spacetime (Z4c formulation)

Coupled with...

- solving the **MHD** (fluids + magnetic fields) on this dynamical spacetime

Plus...

- Nuclear processes (neutrinos, dense nuclear matter EoS,...)



We use our Numerical Relativity + MHD code **GR-Athena++** which uses oct-tree AMR and task-based parallelism. It is based on the public code Athena++.

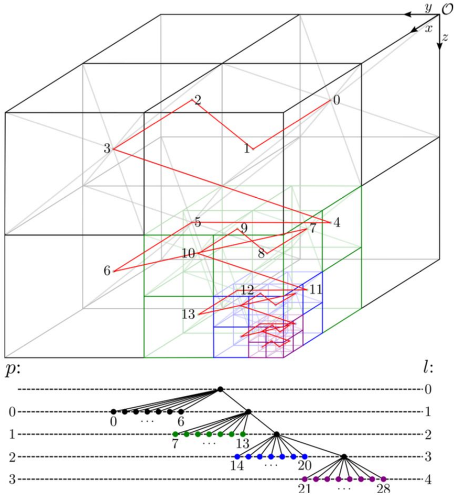
Daszuta+2021, ApJ SS, 257, 2

Cook+2023, arXiv:2311.04989

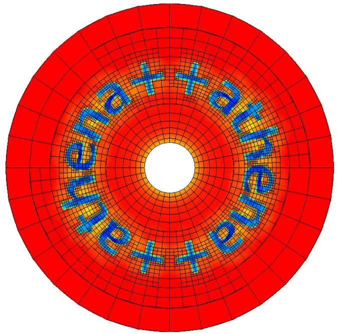
Daszuta+2024, arXiv:2406.09139

We evolve the EE in the Z4c formulation, coupled with the GR Euler Equations written in conservation law form, to exploit high-resolution shock capturing techniques.
Magnetic fields are evolved with the Maxwell equations in the ideal MHD approximation with the Constraint Transport method.

- Mesh refinement is implemented by flagging individual MeshBlocks for refinement. The MeshBlock is destroyed, and replaced with 8 "child" MeshBlocks, each with the same number of points as its parent, but half the spatial extent.



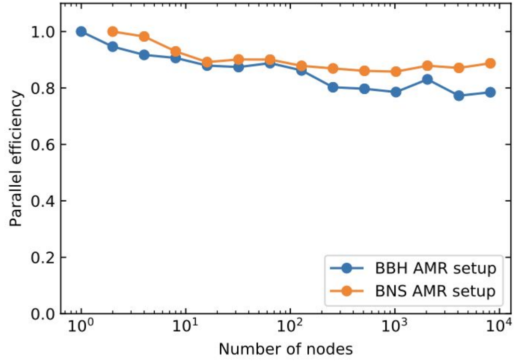
https://www.athena-astro.app/

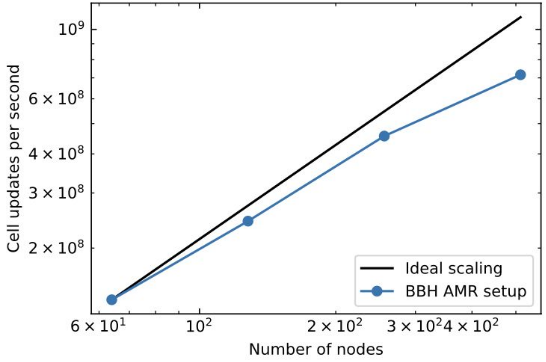


Stone+2020, ApJ SS, 249, 1

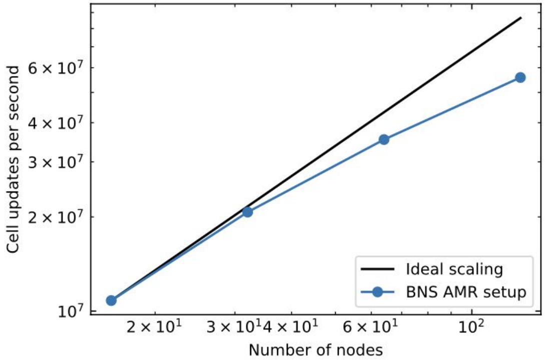
GR-Athena++ leverages the **task-based parallelism** paradigm of Athena++ to achieve excellent scalability

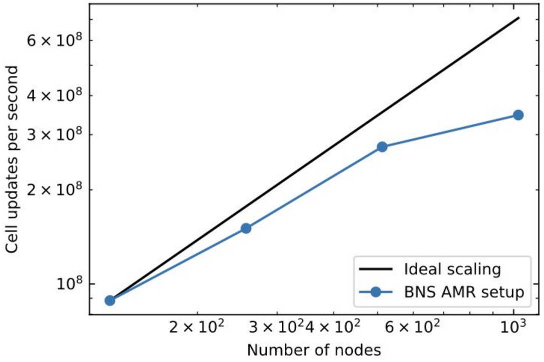
- Strong scaling efficiency above 80% for 256 nodes





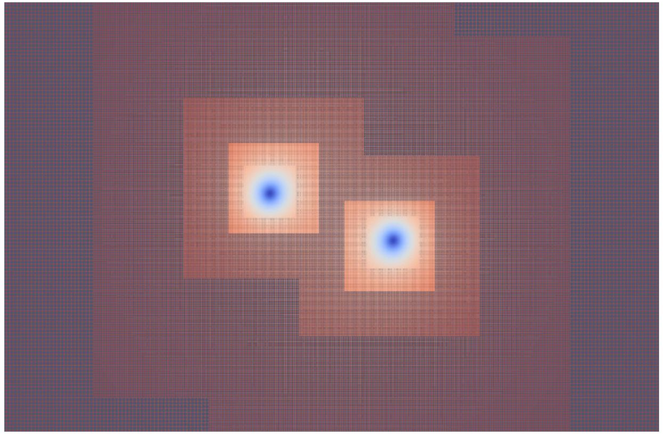
- Weak scaling efficiency better than 80% up to 2048 nodes in a realistic production setup

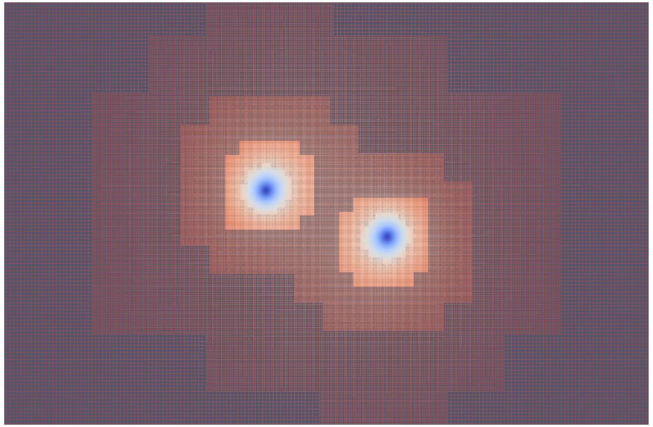


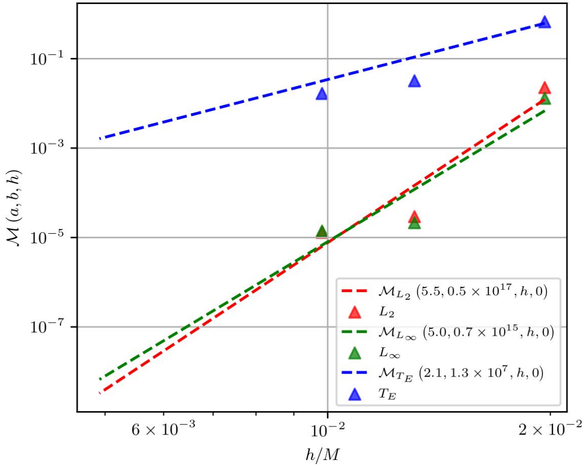


BBH: Comparison of mesh-refinement methods

(Rashti+2024, CQG, 41, 9)



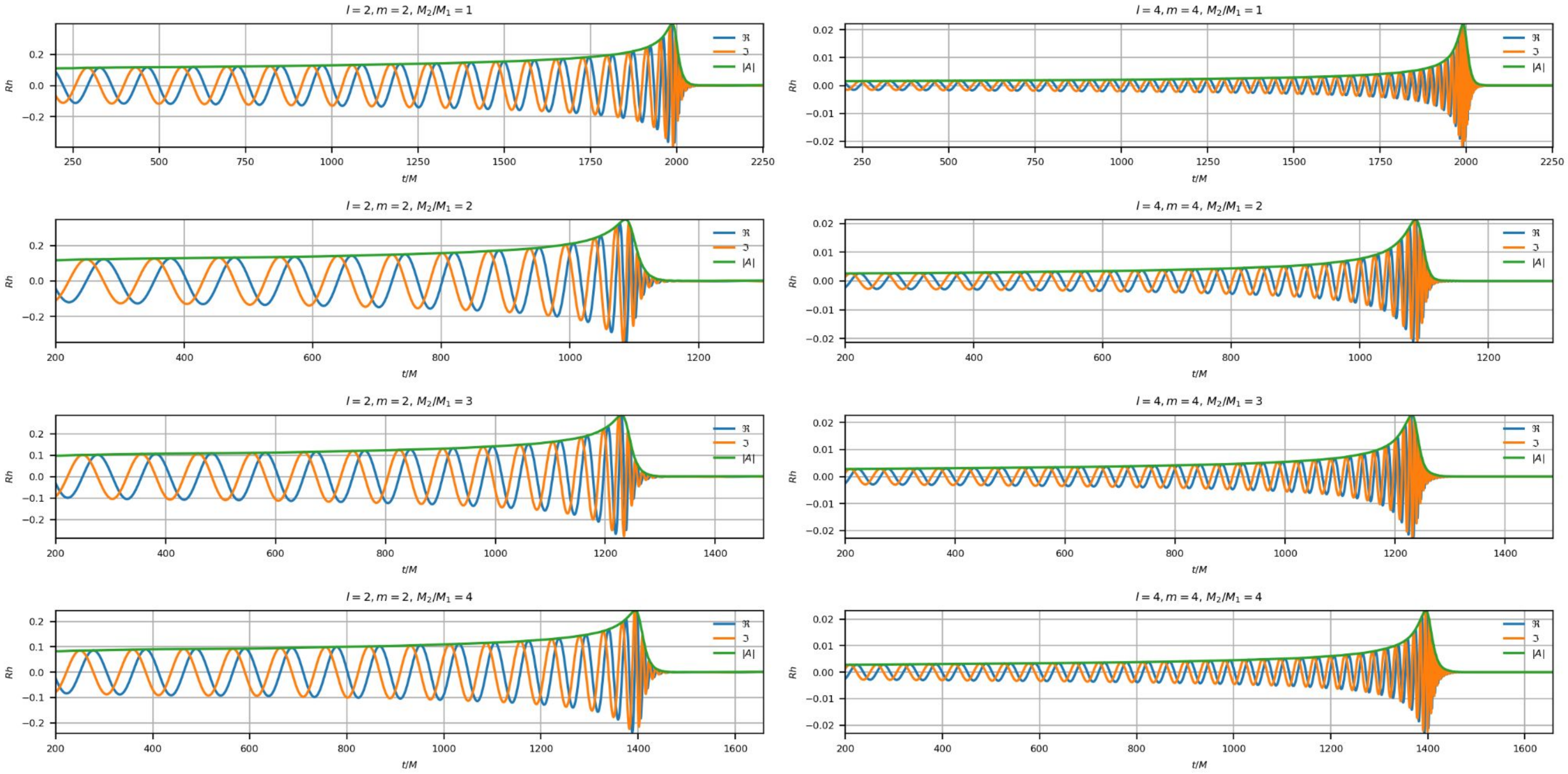




The sphere-in-sphere approach provides the best strategy overall when considering computational cost and the waveform accuracy

BBH: HR simulations to produce GW waveform catalogs with the precision demanded by upcoming gravitational detectors

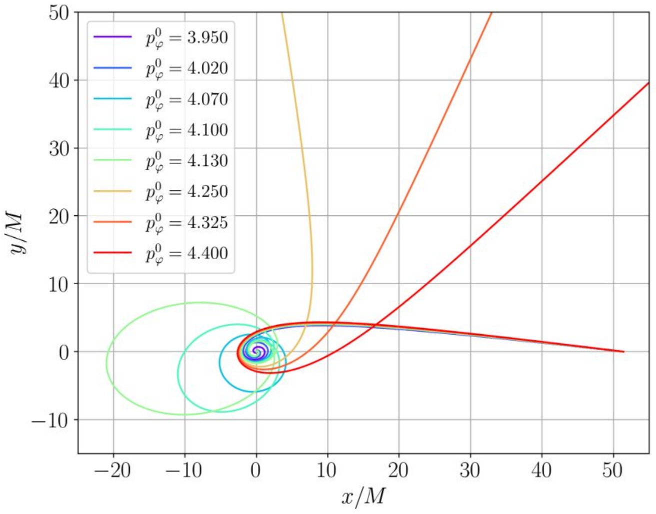
(Rashti+2024, in prep.)

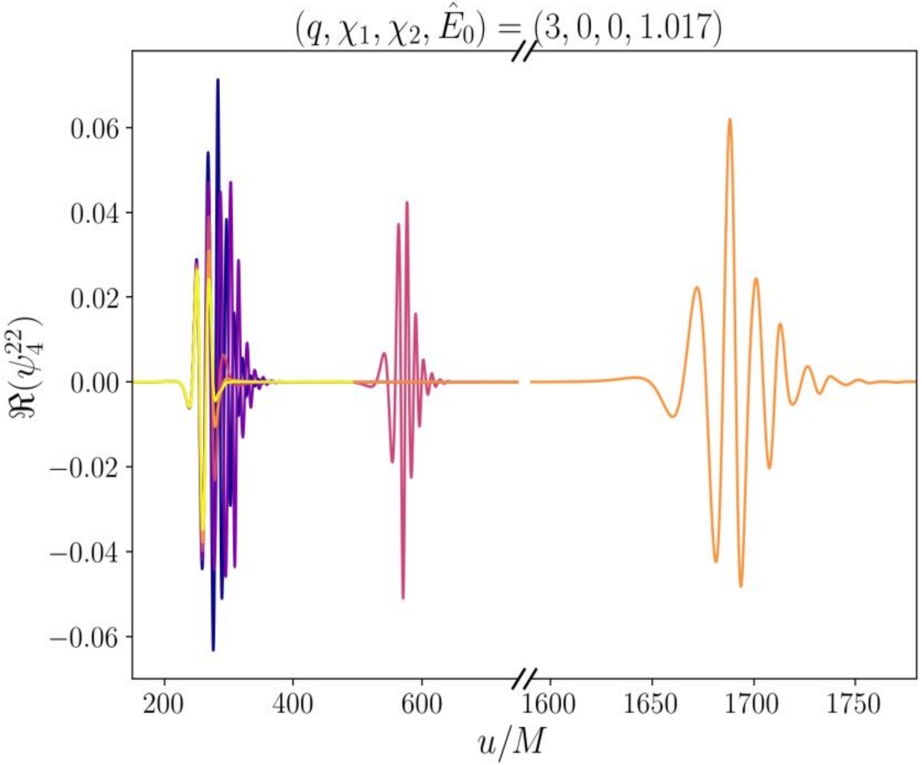


Unbound systems of two black holes and dynamical capture (Albanesi+2024, arXiv:2405.20398)

These results are then used to validate effective-one-body models for dynamical captures and scattering.

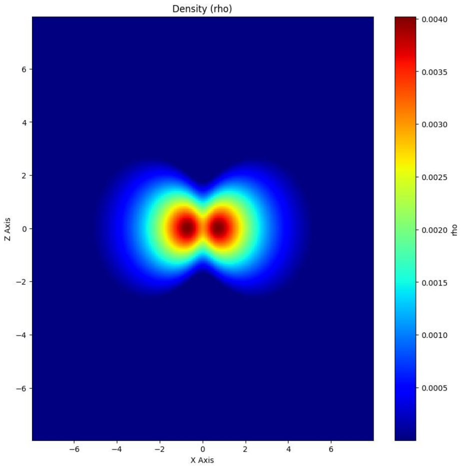
We find good agreement for the waveform phenomenologies, scattering angles, mismatches, and energetics.

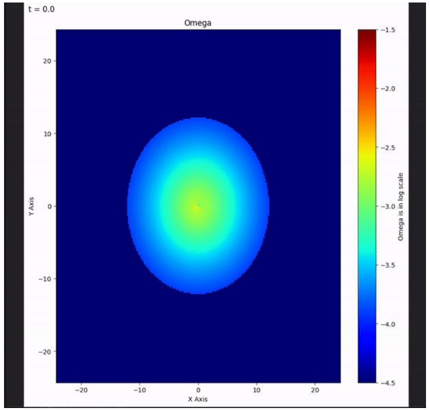




Collapse of differentially rotating hypermassive NS

(Bandyopadhyay, Hammond ++ 2024, in prep)



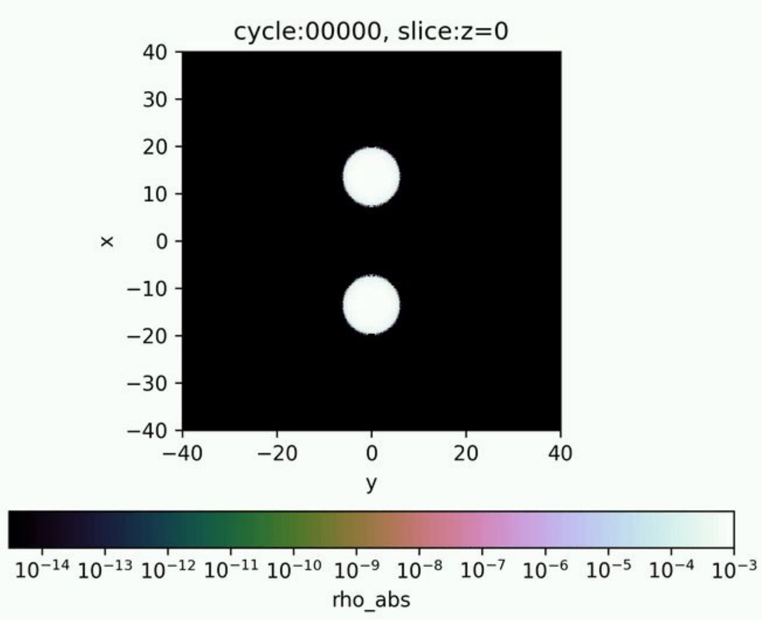


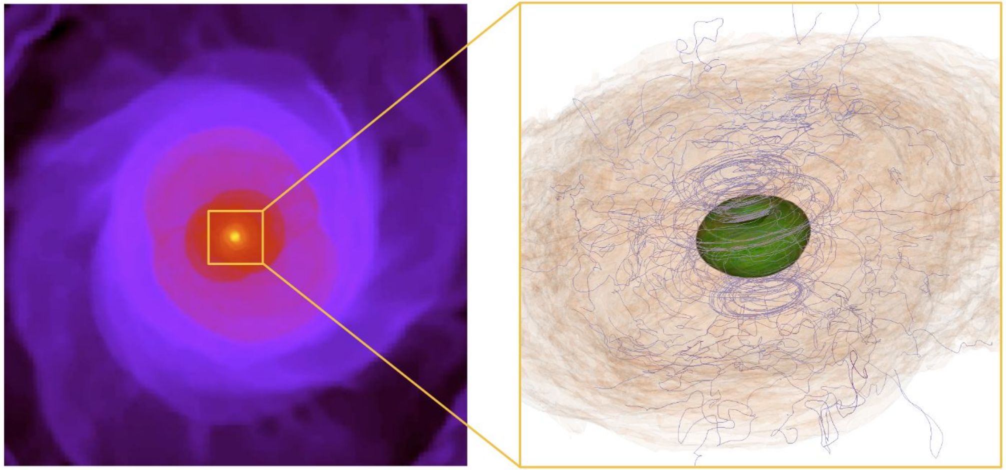
The aim is to study the **magnetorotational instability** and the **turbulence** it induces by looking at distinct patterns in the magnetic field, and the interaction between this field and the fluid.

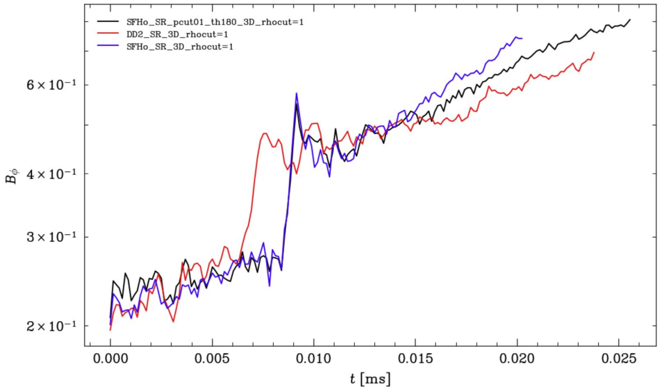
Additionally, we want to measure the **effective shear viscosity** to calibrate future simulations, and finally we will compare our results with 2D simulations in the literature.

Magnetized Binary Neutron Star Mergers

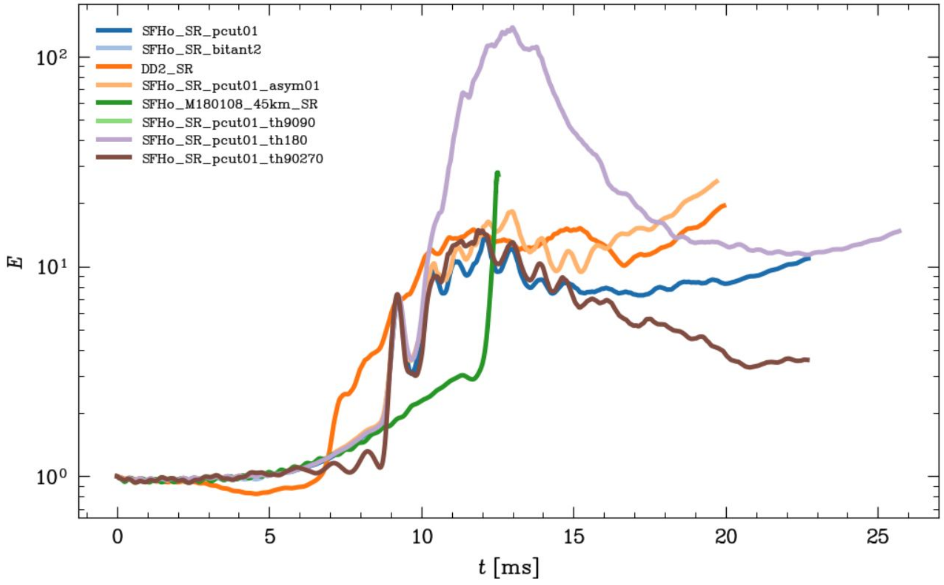
(Gutierrez++2024, in prep)

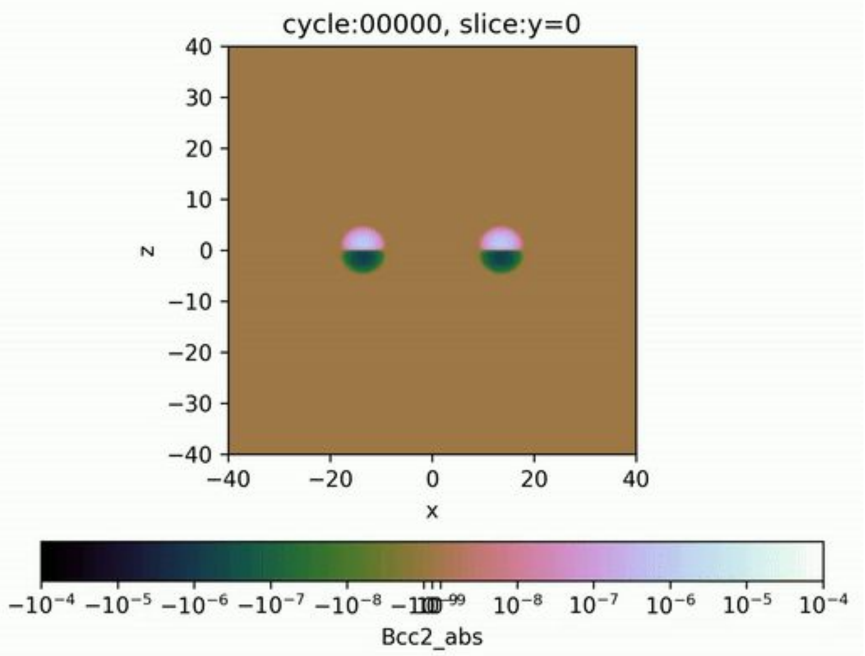






- **We are currently conducting a campaign of BNS simulations with different microphysics and magnetic field structure**





(Gutierrez++2024, in prep)

Future directions

In addition to the current ongoing projects.

We are about to finish the coupling of our code with an **M1 neutrino transport** scheme based on *Radice++2022*.

We are preparing very-high resolution simulations (Texascale Days)

Our next simulations will be performed with the **full physics** required to study **long-term** postmerger BNS remnants, the **ejecta** they produce, the **launching of jets**, etc..