GRMHD evolutions with GR-Athena++

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Motivation

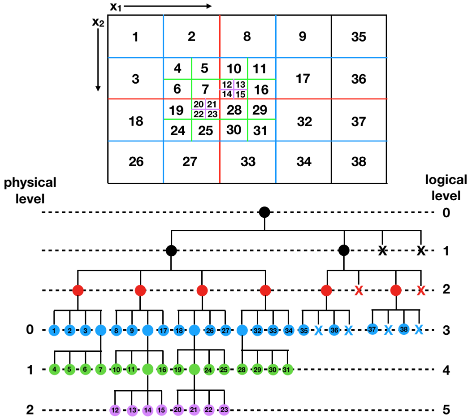
- Gravitational wave (GW) astronomy relies on accurate numerical relativity waveform data to perform detections and parameter estimation of compact binary GW sources.
- As GW detectors reach design sensitivity, and with the prospect of third generation detectors approaching we can expect to see sufficiently loud signals from BNSs that systematic errors in waveform models dominate statistical error [Gamba+ 2020]

Motivation

- To model GW and EM counterparts arising from BNS mergers we need to model a range of physical processes at varying scales.
    - Gravity (GR)
    - MHD
    - Strong and weak nuclear processes (dense nuclear matter EoS, neutrinos, r-process nucleosynthesis)
- We require NR codes capable of performing high-resolution large simulations with AMR which scale efficiently to exploit modern exascale HPC architecture.

GR-Athena++

- Athena++ [a] is a public C++ code designed for solving GRMHD problems in stationary spacetimes [Stone+ 2020] , using Constrained Transport, with angular dependent radiation transport [White+ 2023]
- Task-based parallelism allows computation to overlap with communication during execution, and an oct-tree block-based AMR provides scaling performance with flexible refinement.

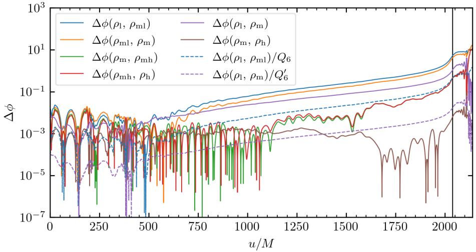


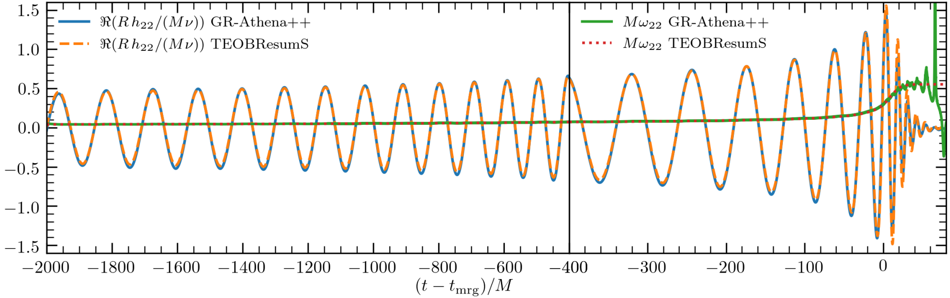
[Stone+ 2020]

[a] https://github.com/PrincetonUniversity/athena

GR-Athena++

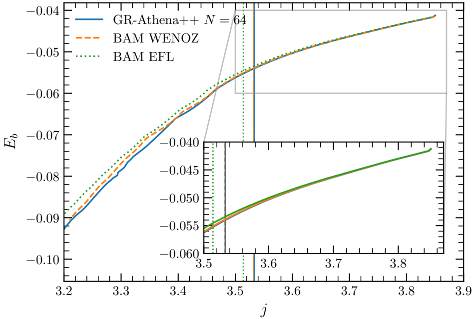
- GR-Athena++ builds on this framework introducing a solver for the Einstein equations on a vertex centred grid, allowing the evolution of dynamical spacetimes such as BBH [Daszuta+ 2021] and BNS, maintaining scaling properties.





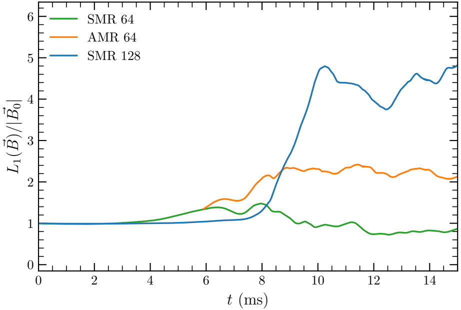
Code tests.

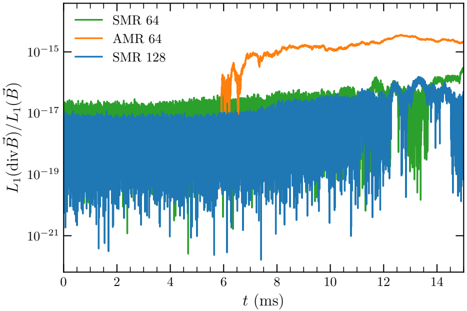
- To validate GR-Athena++ we compare a Binary Neutron Star merger against a similar simulation in the established BAM code [Thierfelder+ 11] , showing good agreement in the energetics of the GW signal emitted, with phase difference converging at 2nd order.
- (WENOZ reconstruction, Gamma law EoS, RePrimAnd [Kastaun+ 20] Con2Prim, LORENE Initial data)



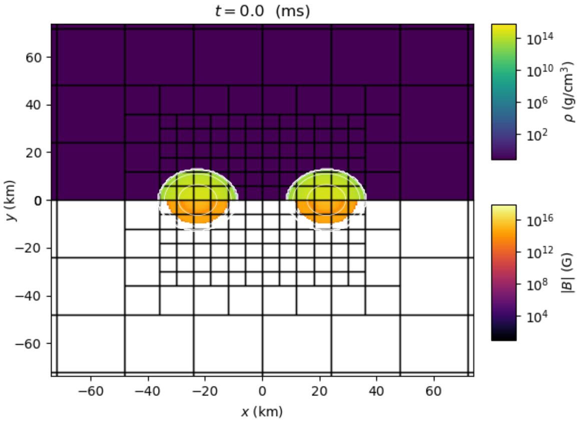
BNS merger - GRMHD

- Increasing resolution better resolves the amplification of the magnetic field as the stars make contact.
- By adding an extra level of AMR we can better resolve the B field amplification for an increase of $\sim< 10\%$ computational load.





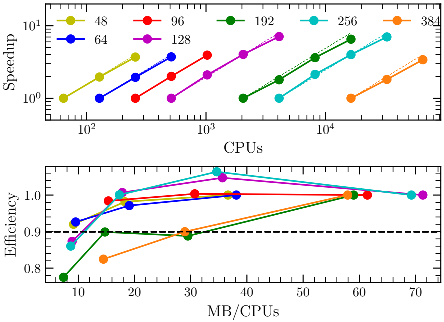
BNS GRMHD

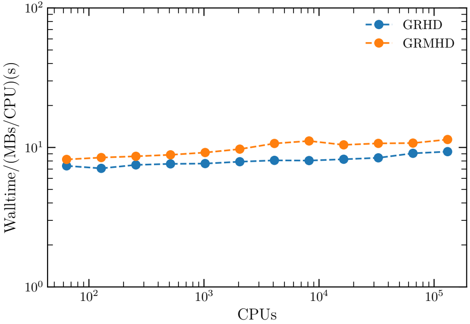


$t = 0.0$ (ms)
60
40
20
0
−20
−40
−60
y (km)
−60
−40
−20
0
20
40
60
x (km)
10^{14}
10^{10}
10^{6}
10^{2}
ρ (g/cm^3)
10^{16}
10^{12}
10^{8}
10^{4}
$|B|$ (G)

Scaling tests

- GR-Athena++ shows strong scaling efficiency (left) of over 90% up to $\mathcal{O}(10^4)$ CPU cores for sufficient computational loads , while maintaining clear weak scaling (right) up to $\mathcal{O}(10^5)$ CPU cores for dynamical GRMHD evolutions.





Conclusions

- We have adapted the Athena++ code to evolve magnetised BNS mergers in dynamical spacetimes with GR-Athena++.
- Strong scaling tests show 90% efficiency for sufficient computational loads, up to $\sim 10^4$ cores.
- Weak scaling holds up to $\sim 1 \times 10^5$ cores.