# GRMHD with Athena++ and its Application to MAD

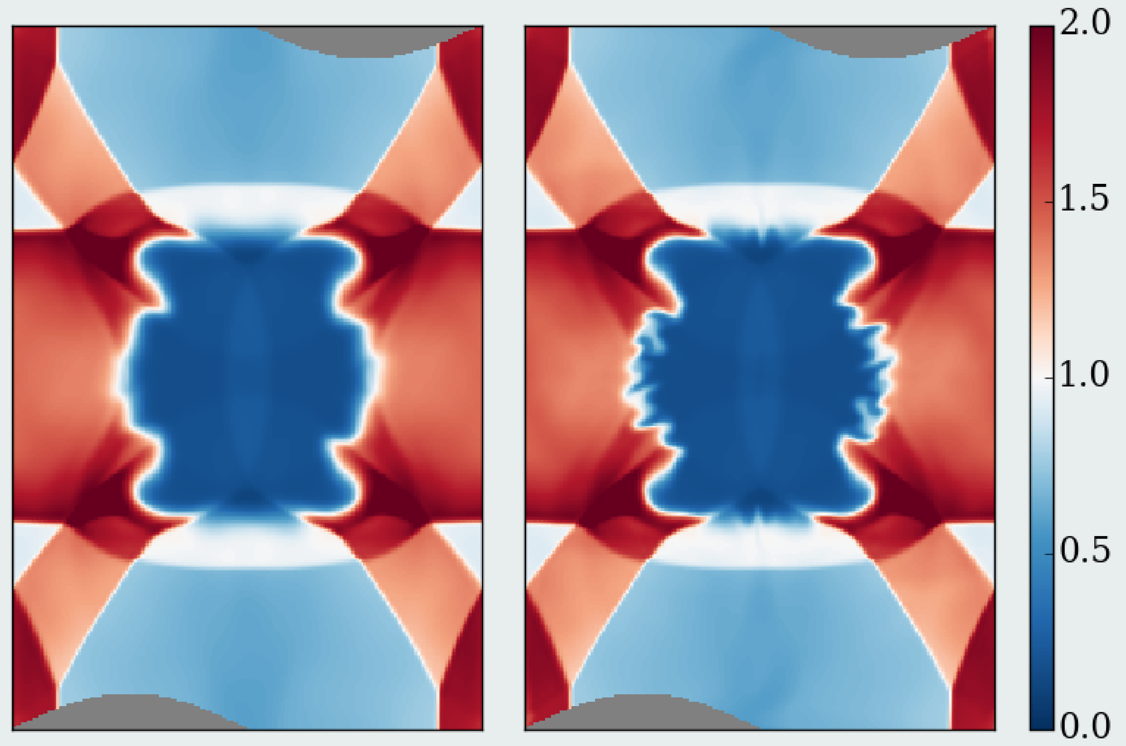
PRINCETON UNIVERSITY

Christopher J. White and James M. Stone

Horizon Collaboration
An NSF Theoretical and Computational Astrophysics Network

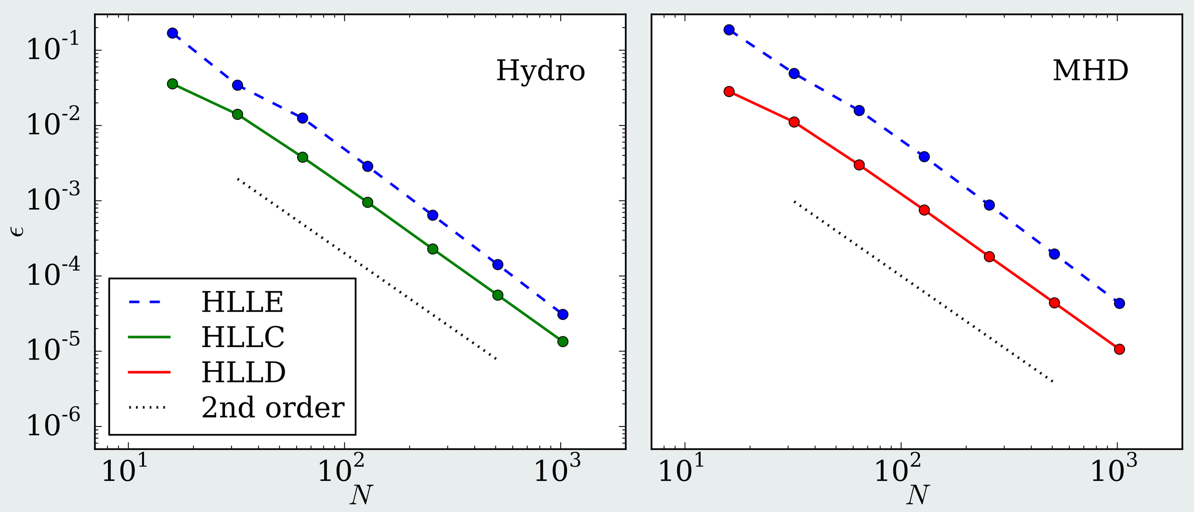
## Advanced Riemann Solvers

- Better solvers → less diffusion




Density of hydro blast wave in "snake" coordinates, using HLLE (left) and HLLC (right).

- HLLC: Captures contact in hydrodynamics
- HLLD: Captures contact and Alfvén in MHD

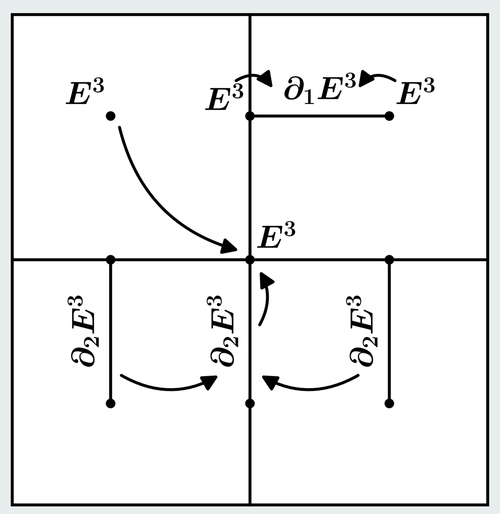



Entropy wave convergence tests in metric with time-space cross terms.

- Method (cf. Pons et al. 1998, Antón et al. 2006):
  - Transform into orthonormal frame at each face
  - Use SR Riemann solvers
  - Transform fluxes back

## Constrained Transport

- Staggered mesh: $\vec{B}$ defined on faces
- GR formulation: Evans & Hawley 1988
- Cartesian: Athena (Gardiner & Stone 2005, 2008)
- Now implemented in GR with Athena++



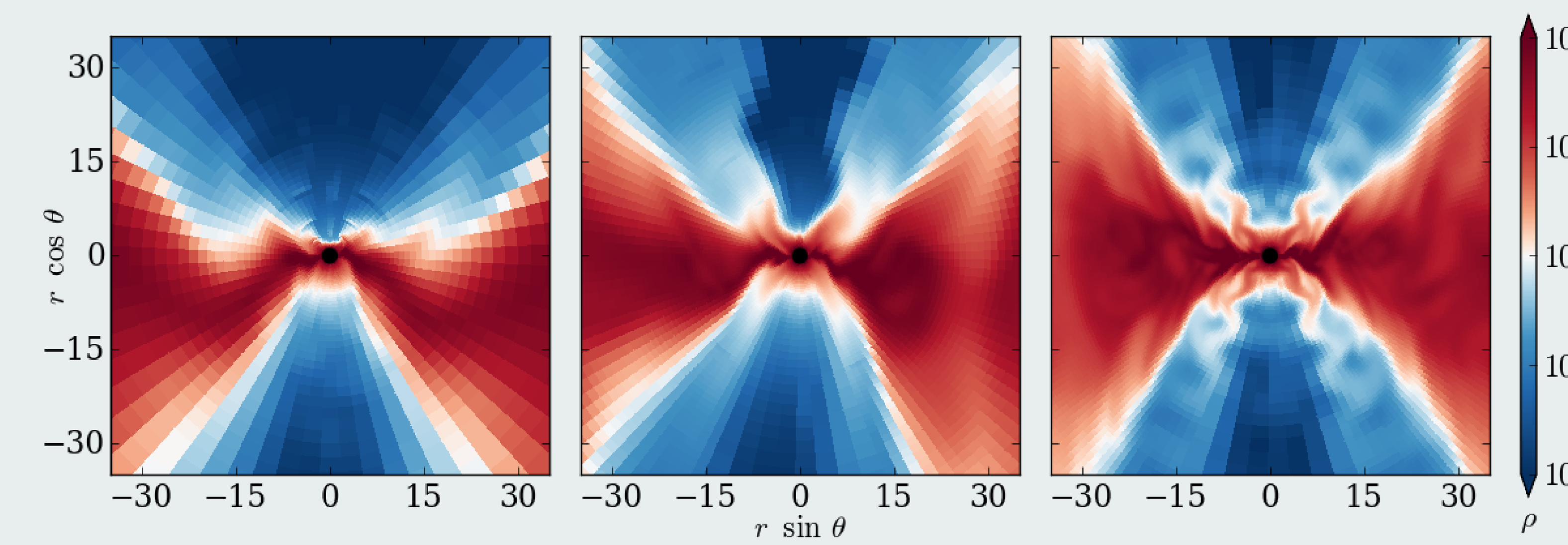

Schematic showing how $\vec{E}$ is calculated on an edge (center) self-consistently with the Riemann fluxes.

## Summary

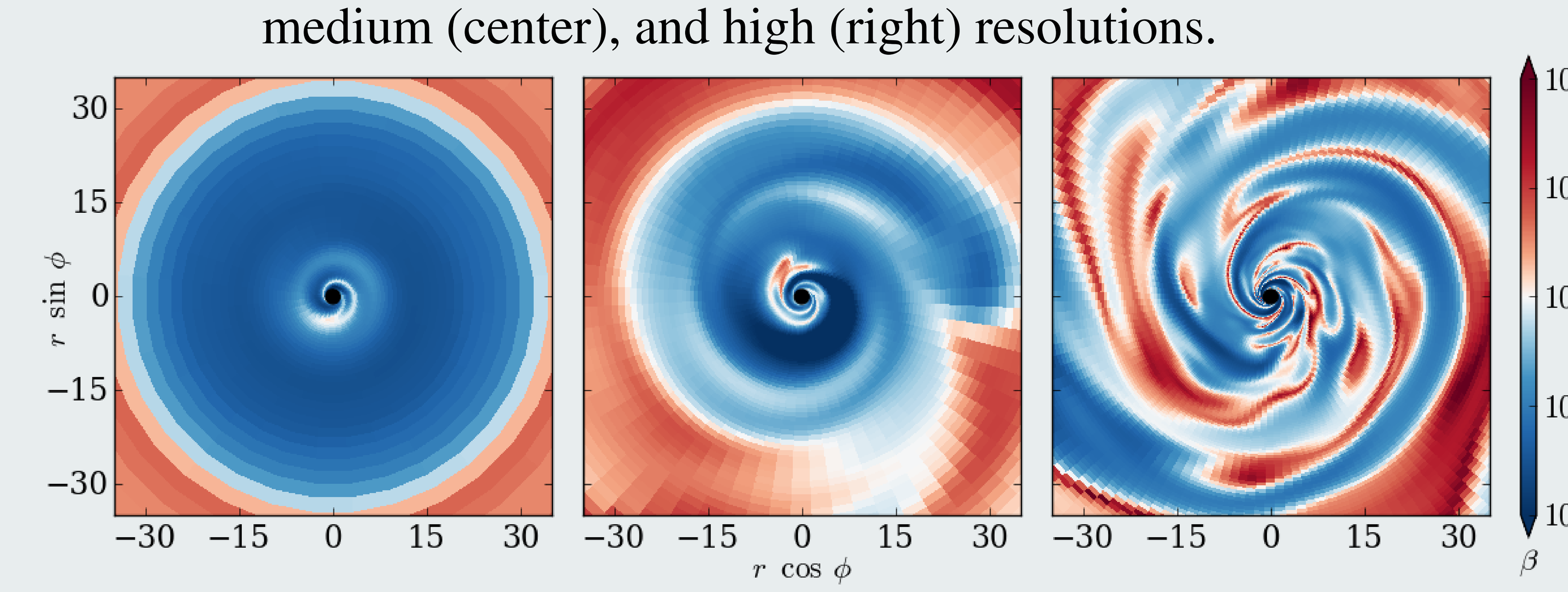
- Extending Athena++ framework to general relativity, while maintaining its advantages in speed and accuracy for ideal MHD
- Goal: Studying accretion flows near black holes in high resolution
- See arxiv:1511.00943 for code details

## Magnetically Arrested Disks at Different Resolutions

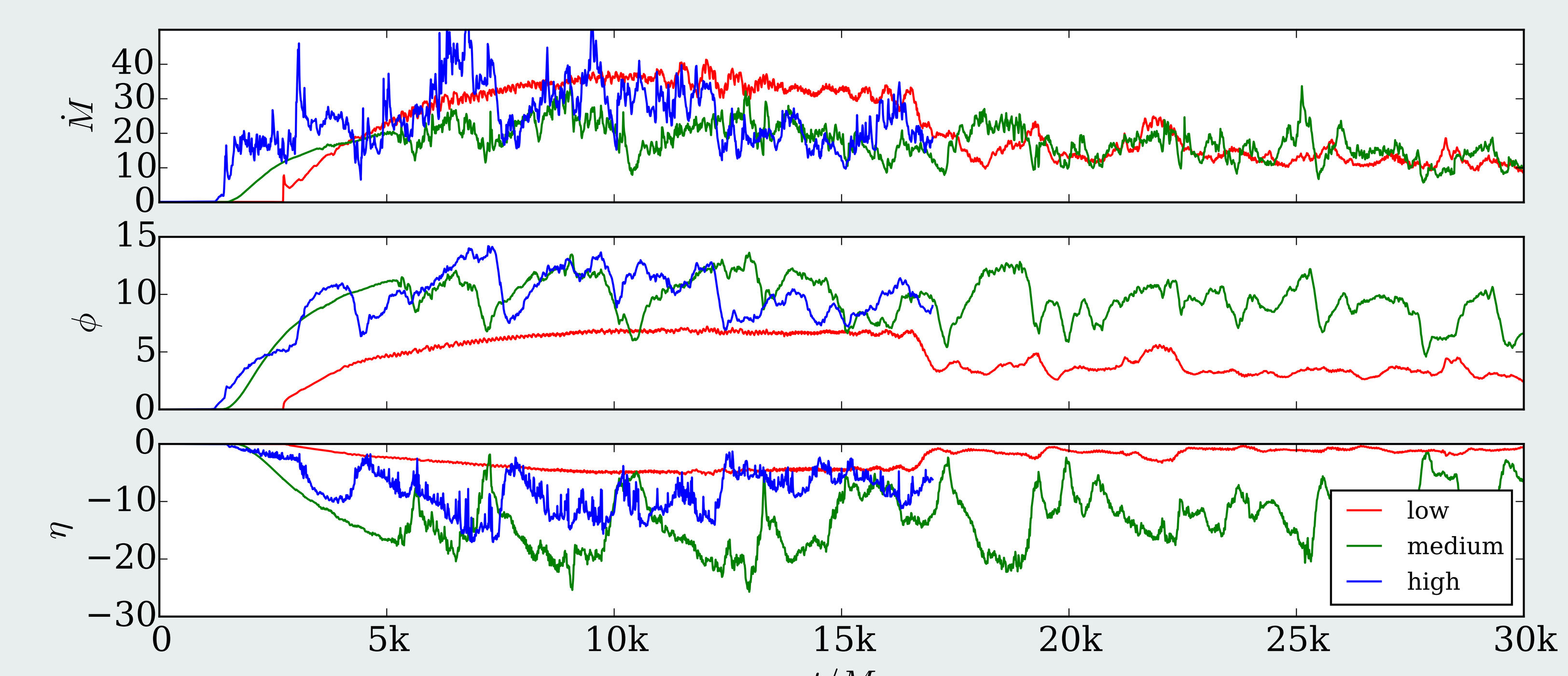
- Test of code: Can we reproduce results in a relativistic, turbulent, magnetized flow?
- Exploring MAD at high resolutions: Are there non-axisymmetric instabilities that prevent choking of flow?
- Initial conditions of Tchekhovskoy, Narayan, & McKinney 2011
- Resolutions $N_r \times N_\theta \times N_\phi$: $96 \times 32^2$, $192 \times 64^2$, $384 \times 128^2$
- Preliminary results below




Polar slice of density at $t = 14{,}000\,M$ for low (left), medium (center), and high (right) resolutions.



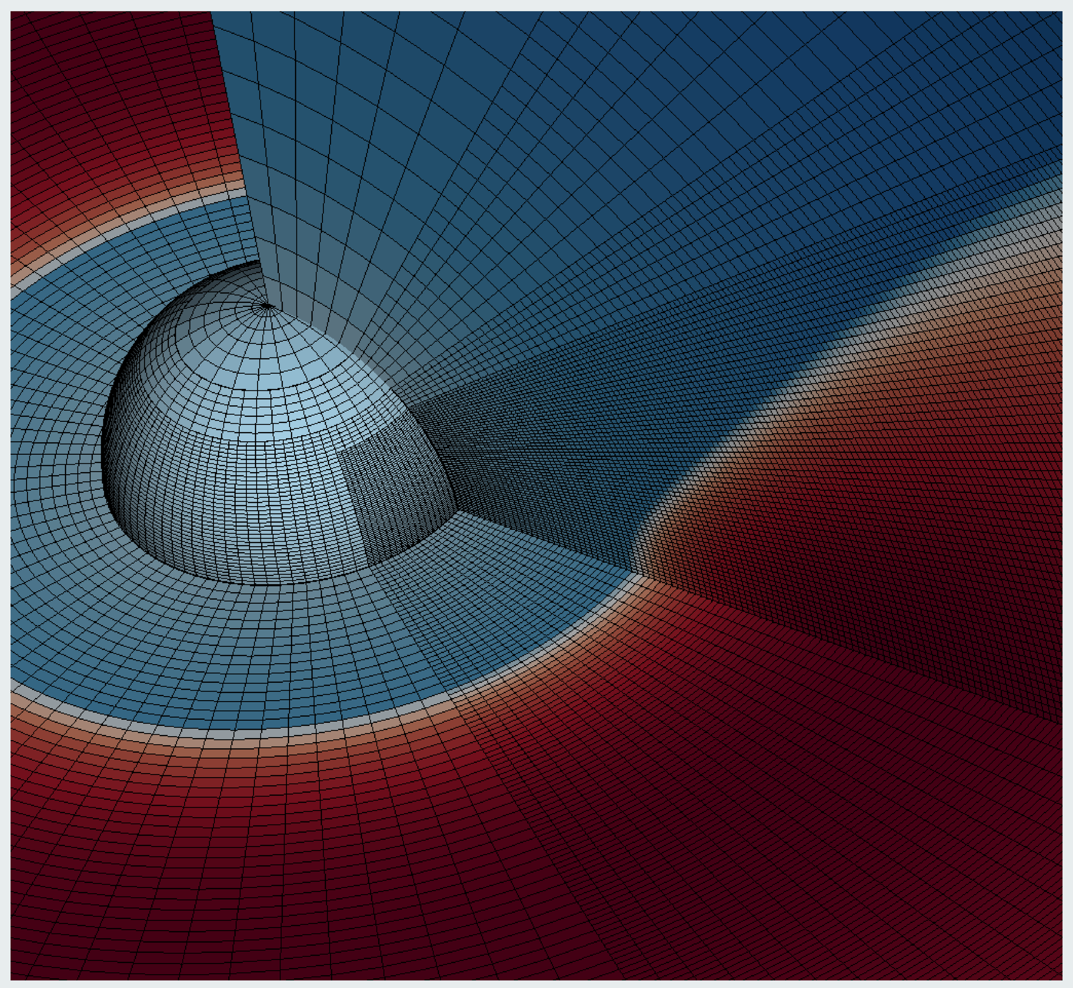

Equatorial slice of $\beta$ at $t = 14{,}000\,M$ for low (left), medium (center), and high (right) resolutions.




Accretion rate, flux threading horizon, and efficiency for three resolutions.

## Mesh Refinement and Polar Coordinates

- Static and adaptive mesh refinement supported
- Coarsen grid near poles → larger timestep
- Cells communicate across polar boundary → no need for artificial boundary condition



Example polar grid with equatorial refinement.

## Performance

- Zone updates per second, single core, 2.5 GHz Ivybridge

| | | SR | GR |
|---|---|---|---|
| Hydro | LLF | 1,300,000 | 380,000 |
| | HLLC | 860,000 | 330,000 |
| MHD | LLF | 320,000 | 290,000 |
| | HLLD | 120,000 | 120,000 |

- Flat scaling to many cores