Athena++: A New GRMHD Code for Black Hole Accretion

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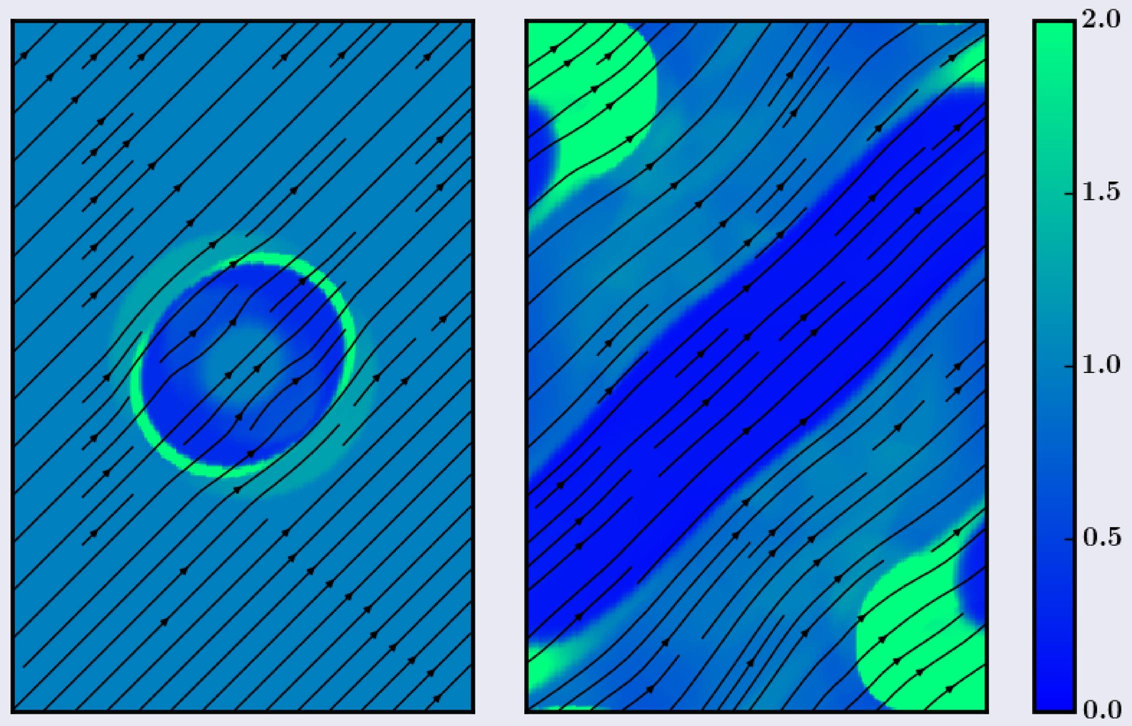
Advanced Riemann Solvers

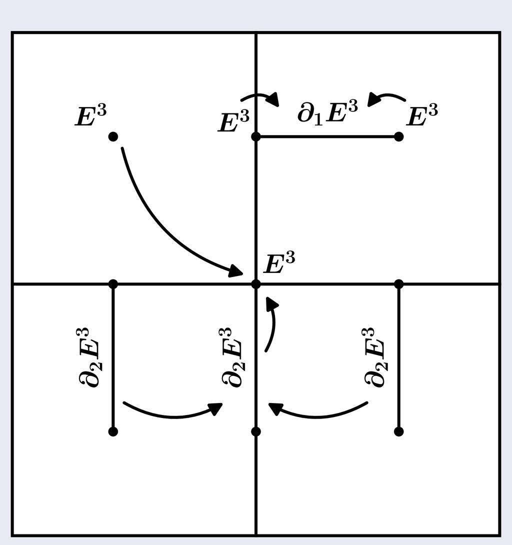
- Many codes use local Lax-Friedrichs and HLLE
- HLLC: Captures contact in hydrodynamics
- HLLD: Captures contact and Alfvén in MHD
- Better solvers → less diffusion
- Method (Pons et al. 1998, Antón et al. 2006):
  - Transform into orthonormal frame at each face
  - Use SR Riemann solvers
  - Transform fluxes back



Magnetized blast wave in sinusoidal coordinates, showing gas pressure and magnetic field, computed using HLLD. The solution matches that obtained in Minkowski coordinates.

Constrained Transport

- Keeps $\nabla \cdot \vec{B} = 0$, natural discretization of Stokes' law
- Formulated in GR (Evans & Hawley 1988)
- Staggered mesh: $\vec{B}$ defined on faces
- Implementation proven in Athena (Gardiner & Stone 2005, 2008)



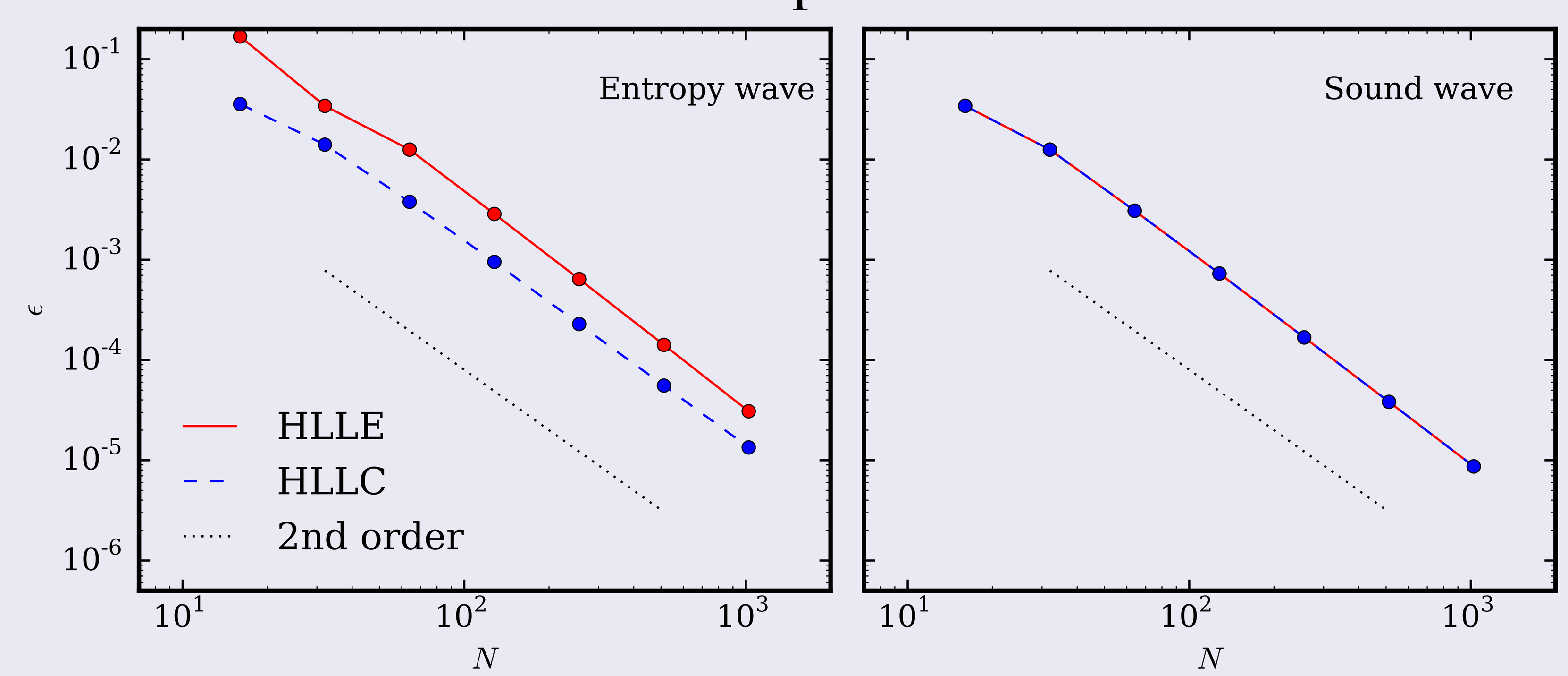
Schematic showing how $\vec{E}$ is calculated on an edge (center) self-consistently with the Riemann fluxes. Fields at faces and cell centers are differenced to calculate gradients, which are upwinded back to faces. These contribute to calculating the edge values.

Summary

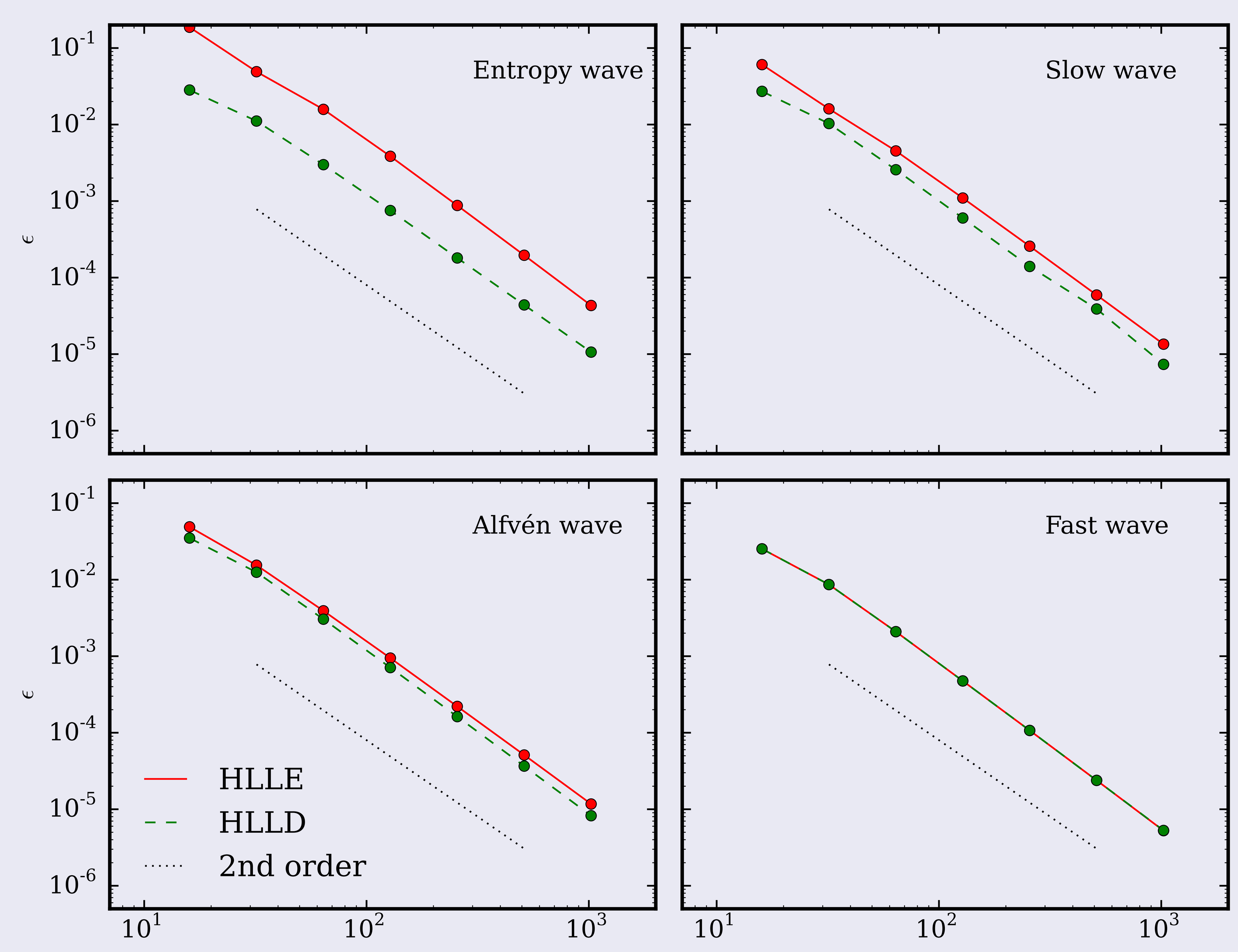
- Extending Athena to **general relativity**, while maintaining its advantages in **speed** and **accuracy** for ideal MHD.
- Goal: studying **radiation-dominated** accretion flows near black holes.

Convergence Tests

- 2nd-order (piecewise linear) spatial reconstruction
- 2nd-order timestepping (van Leer integrator)
- Tested with linear waves
  - Vector of primitives P obeys $\partial_t P + A \partial_x P = 0$
  - Perturb background with eigenvectors of A
  - Done in coordinates with time-space terms in metric



Hydrodynamics convergence tests. For waves propagating slower than the sound speed, HLLE is more diffusive and less accurate than HLLC.



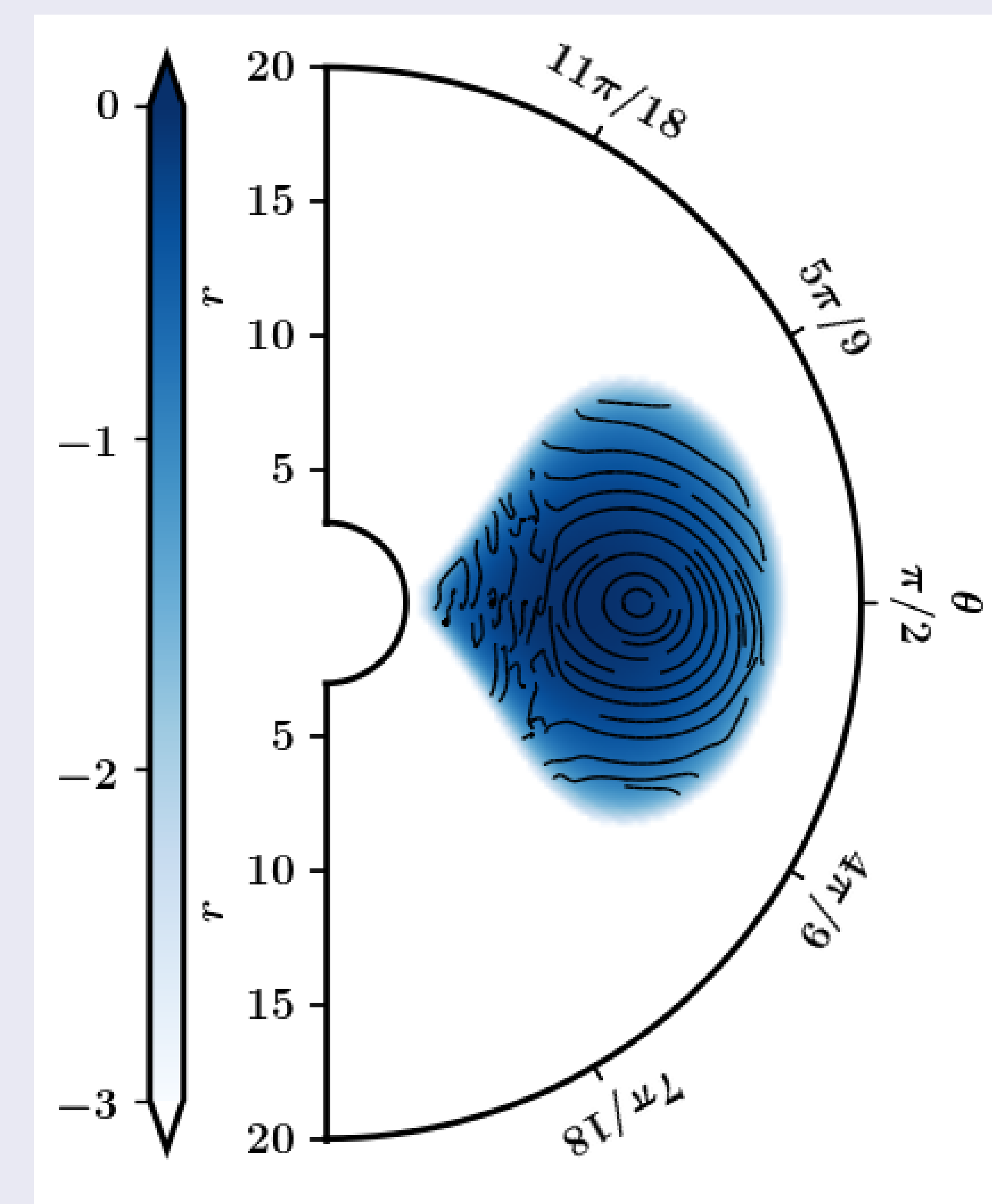
MHD convergence tests. Again a better Riemann solver leads to lower errors, by a factor of almost 5 in the entropy wave case.

Performance

- Key goal: fast and scalable
- Zone updates per second
  - 2.5 GHz Ivybridge, single core

		SR	GR
Hydro	HLLE	1,500,000	1,000,000
	HLLC	1,500,000	1,000,000
MHD	HLLE	490,000	300,000
	HLLD	150,000	100,000

- Further performance improvement expected



Density in magnetized Fishbone-Moncrief (1976) torus around Schwarzschild black hole. The torus has less azimuthal velocity than needed to resist infall, and it has been given a poloidal magnetic field. This shows the beginning of accretion at $t = 30M$.

Looking Forward

- Algorithms
  - Adaptive mesh refinement
  - Radiative transfer
- Applications
  - Bardeen-Petterson effect
  - Tidal disruption