Title: Modeling Luminous Black Hole Accretion Flows with AthenaK

Speakers: James Stone

Collection/Series: Magnetic Fields Around Compact Objects Workshop

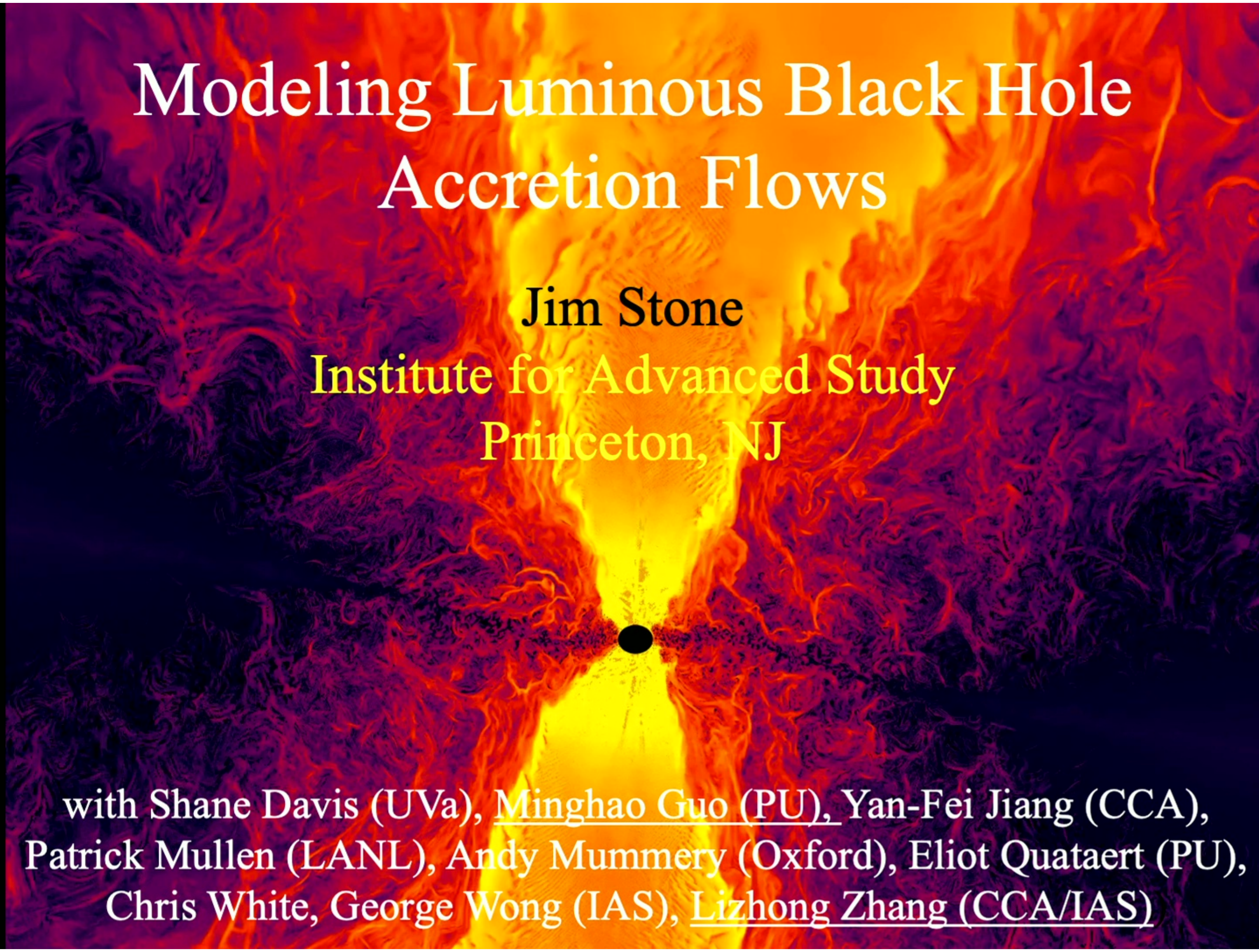
Subject: Strong Gravity

Date: March 26, 2025 - 9:45 AM

URL: https://pirsa.org/25030074

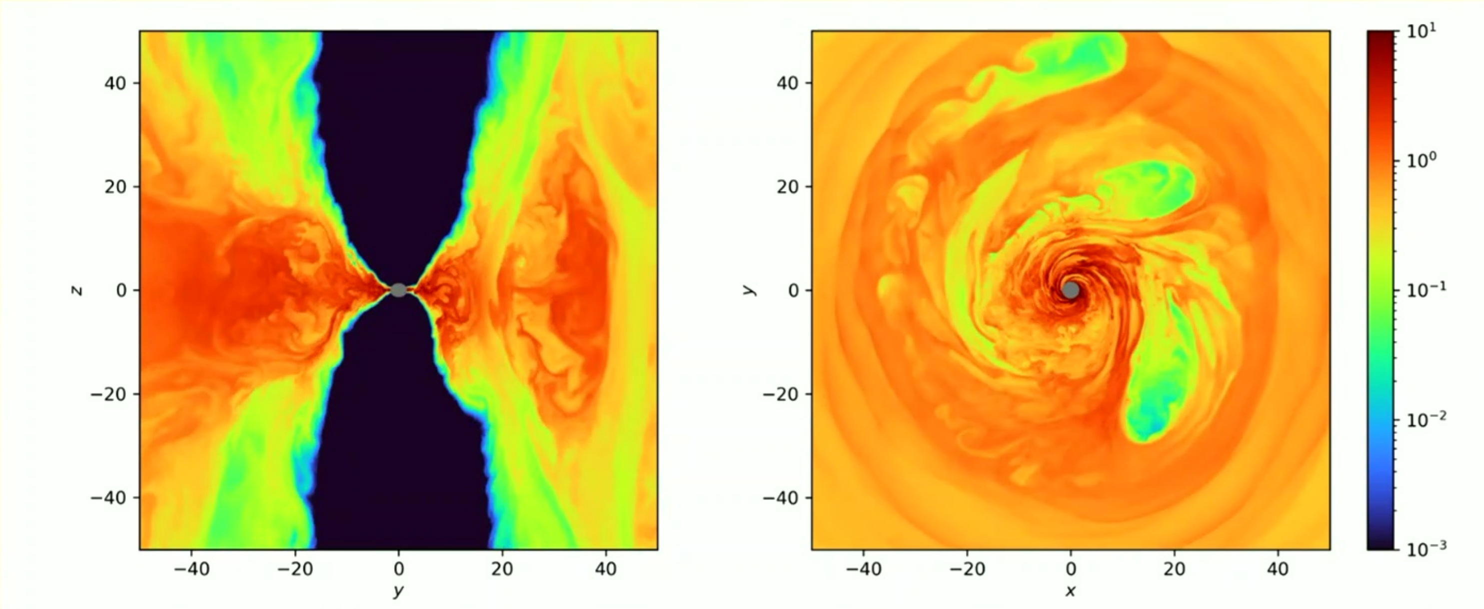
Abstract:

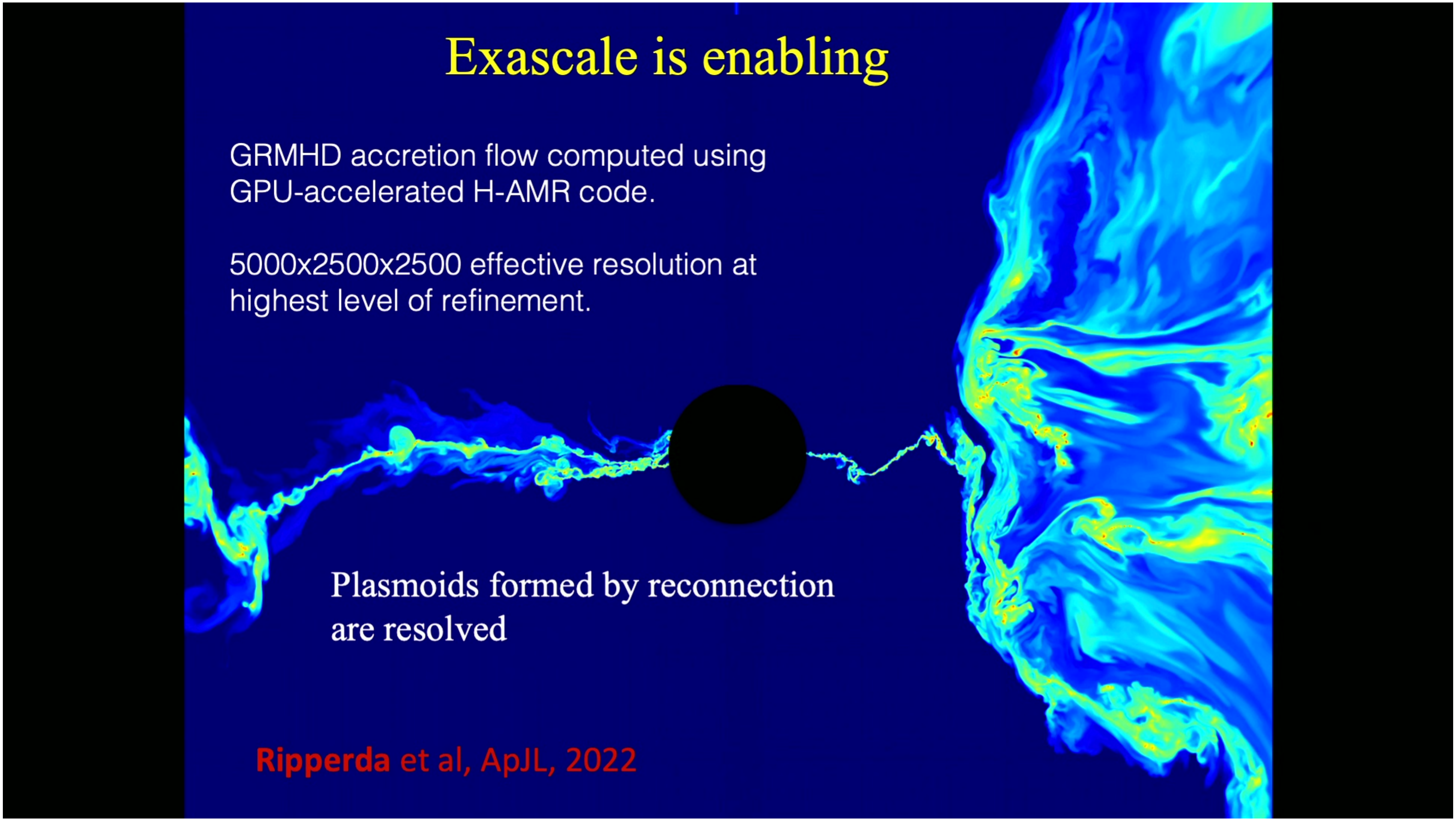
A new version of the Athena++ AMR MHD code implemented using the Kokkos library for performance-portability will be described. The code is being used for a variety of problems related to accretion onto (and merger of) compact objects. This talk will focus on results from general relativistic radiation MHD models of accretion in luminous systems such as X-ray binaries and AGN. The models allow observationally important quantities such as the radiative efficiency, variability, and kinetic feedback in winds to be measured over a range of luminosities, from sub-Eddington to highly super-Eddington. A new "cyclic-zoom" approach for modeling such flows over very long time scales will also be briefly introduced.


Modeling Luminous Black Hole Accretion Flows
Jim Stone
Institute for Advanced Study
Princeton, NJ
with Shane Davis (UVa), Minghao Guo (PU), Yan-Fei Jiang (CCA),
Patrick Mullen (LANL), Andy Mummery (Oxford), Eliot Quataert (PU),
Chris White, George Wong (IAS), Lizhong Zhang (CCA/IAS)

Computational modeling of GRMHD accretion

- Numerical methods for solving the GRMHD equations have become robust and reliable (HARM, H-AMR, BHAC, etc.)
- Enables 3D time-dependent models of the nonlinear regime of the magneto-rotational instability (MRI) and accretion
- ***Example:*** starting from a torus, strongly magnetized (MAD) flow at late times ($t > 10^4$ M) around a rapidly spinning black hole




Exascale is enabling
GRMHD accretion flow computed using GPU-accelerated H-AMR code.
5000x2500x2500 effective resolution at highest level of refinement.
Plasmoids formed by reconnection are resolved
Ripperda et al, ApJL, 2022

AthenaK MHD code

- Complete re-write of Athena++ (Stone 2020) using Kokkos
- Full AMR framework, various physics solvers
  - Newtonian/SR/GR hydro and MHD (Stone+ 2024)
  - Dynamical spacetimes using Z4c formalism (Zhu+ 2024)
  - GRMHD in dynamical spacetimes (Fields+ 2024)
  - Relativistic radiation transport (White+ 2023)
  - Particles: CRs, Lagrangian tracers, (MHD-PIC?)
- Publicly available on GitHub

Performance portability: (measured in mega-cell-updates-per-second)

Table 1. Performance of `AthenaK` on various devices

	Apple M1 pro (8 cores)	Intel Xeon Gold 6326 (32 cores)	NVIDIA V100	NVIDIA A100	AMD MI250	NVIDIA H100	NVIDIA Grace Hopper
hydro	34	63	298	614	405	677	1077
MHD	11	33	158	298	190	290	565

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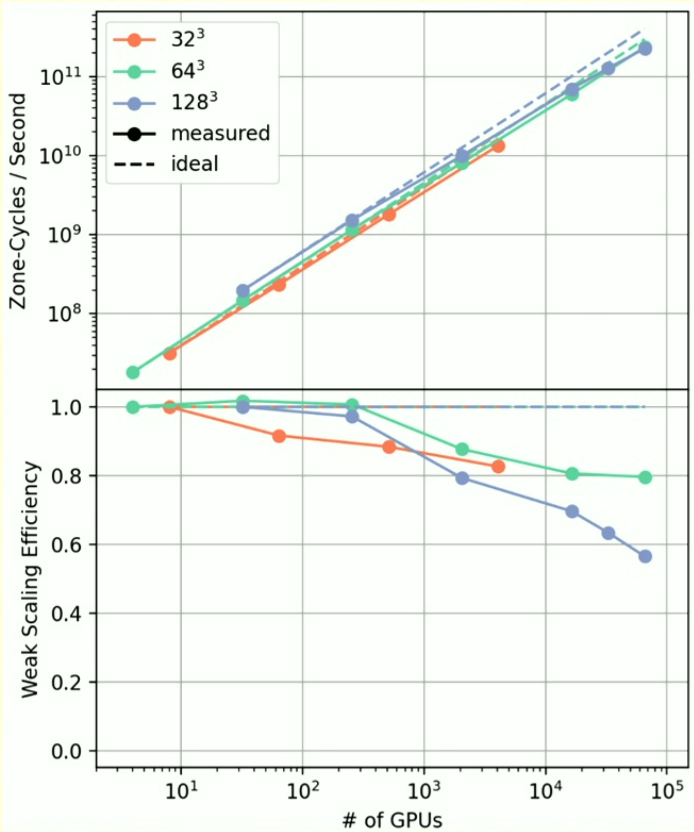
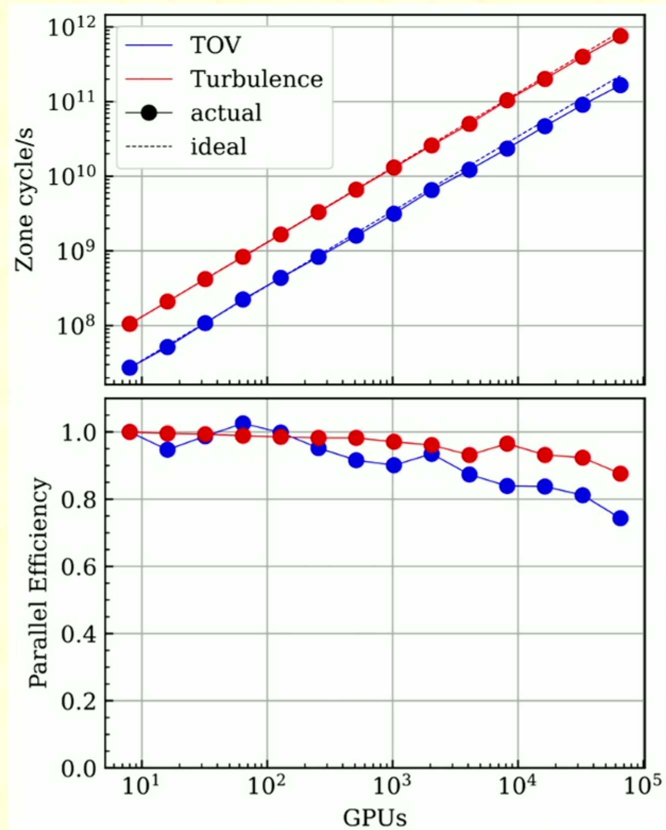
10^9 zone updates per second on a single device!

Excellent weak scaling



NR+AMR solver
(Zhu+ 2024)

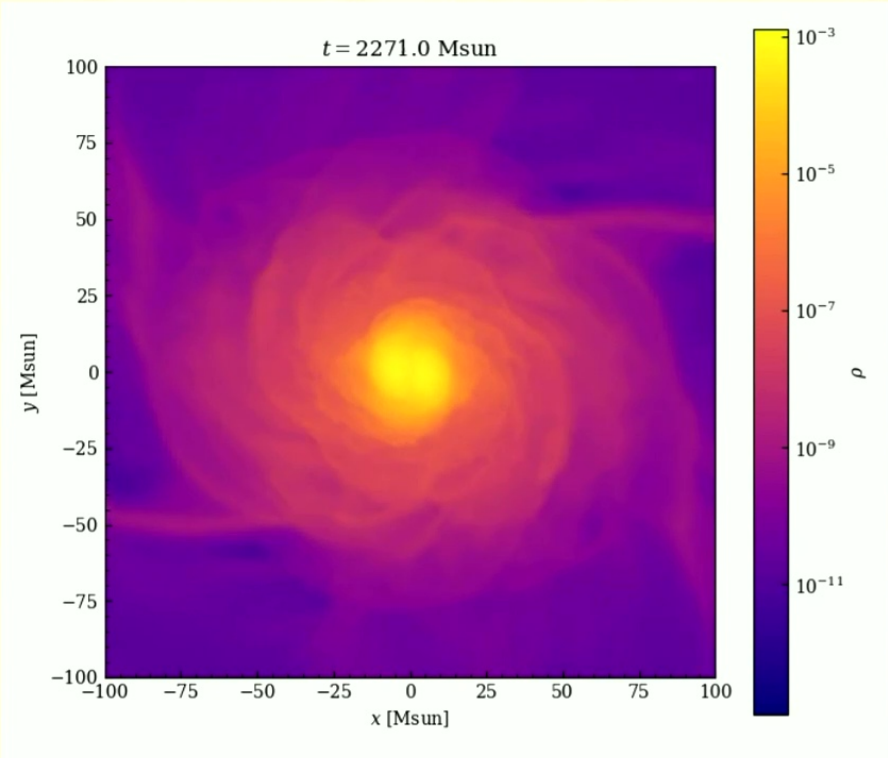


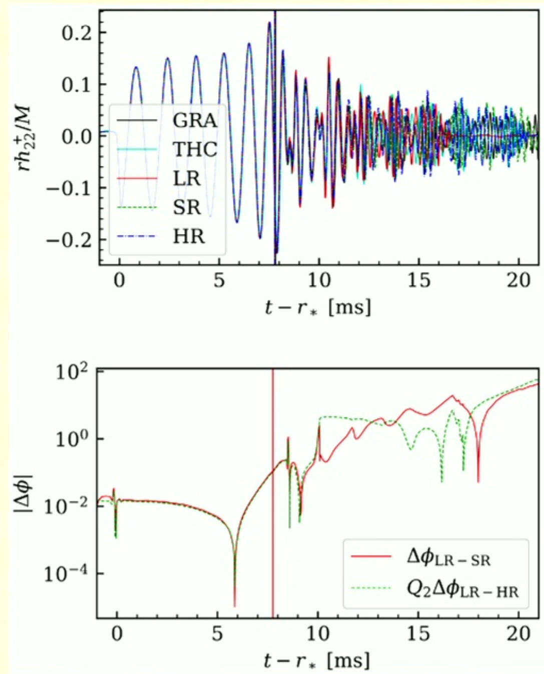
GRMHD in dynamical spacetime
(Fields+ 2024)

Binary neutron star mergers

(work led by J. Fields, D. Radice et al.)

- New GRMHD solver based on Valencia formulation
- Equal mass NSs on quasi-circular orbit, total mass 3.25 M_{sun} ; polytropic EOS
- 7 levels of AMR, resolutions 277m up to 138m on finest level
- Lowest resolution required about 24h on 16 GPUs





2nd-order convergence of GW phase before merger

Exascale enables radiation physics

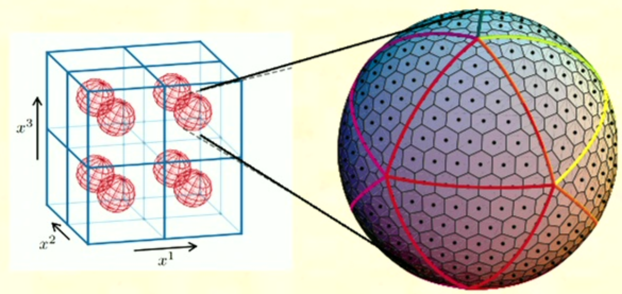
Black hole accretion flows with luminosities $L/L_{Edd} > 10^{-2}$ are in the radiation-dominated regime and must be modeled with radiation GRMHD.

RT method based on a finite-volume discretization of the time-dependent covariant transfer equation (Davis & Gammie 2020; White et al. 2023):

$$\frac{\partial(n^t n_t I_\nu)}{\partial t} + \frac{1}{\sqrt{-g}}\frac{\partial}{\partial x^i}\left(\sqrt{-g}n^i n_t I_\nu\right) - \frac{1}{\sin\zeta}\frac{\partial}{\partial\zeta}(n_\zeta n_t I_\nu) + \frac{\partial}{\partial\psi}(n_\psi n_t I_\nu) + \frac{\partial}{\partial\nu}(n_\nu n_t I_\nu) = n_t(j_\nu - a_\nu I_\nu)$$

Specific intensity discretized in angle using geodesic mesh (e.g. Randall et al. (2002)

More uniform coverage of solid angle
Can be extended to adaptive angular meshes



Very different than M1 method used previously:
McKinney+ 2013; 2017, Sadowski+ 2013; 2017, Fragile+2016; Liska+ 2022; 2023

Parameter Survey of Stellar Mass BH Accretion

A. Initialized with Chakrabarti torus

B. Parameter Survey:

1. Eddington Ratio:

   Super-Eddington: 100 ×, 10 ×

   Near-Eddington: 1 ×

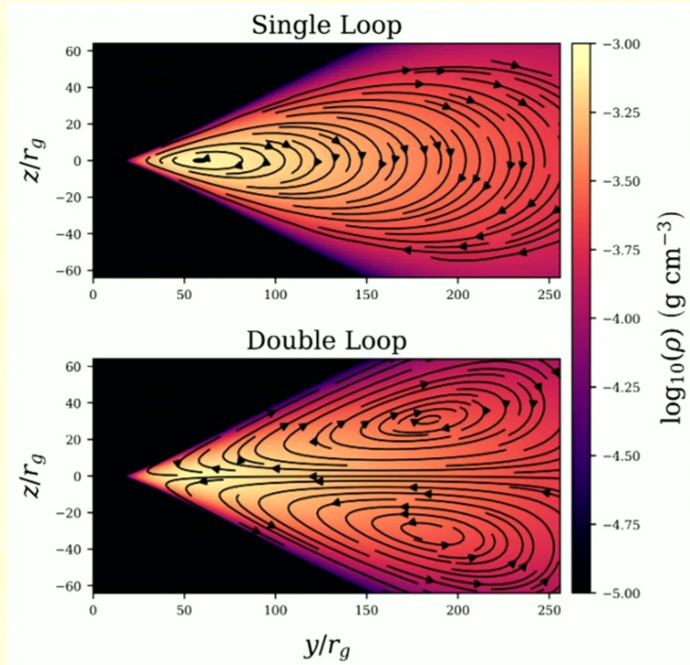
   Sub-Eddington: 0.1 ×, 0.01 ×

2. Black Hole Spin:

   a=0.3, a=0.9375

3. Magnetic Field Topology:

   Single-Loop, Double-Loop

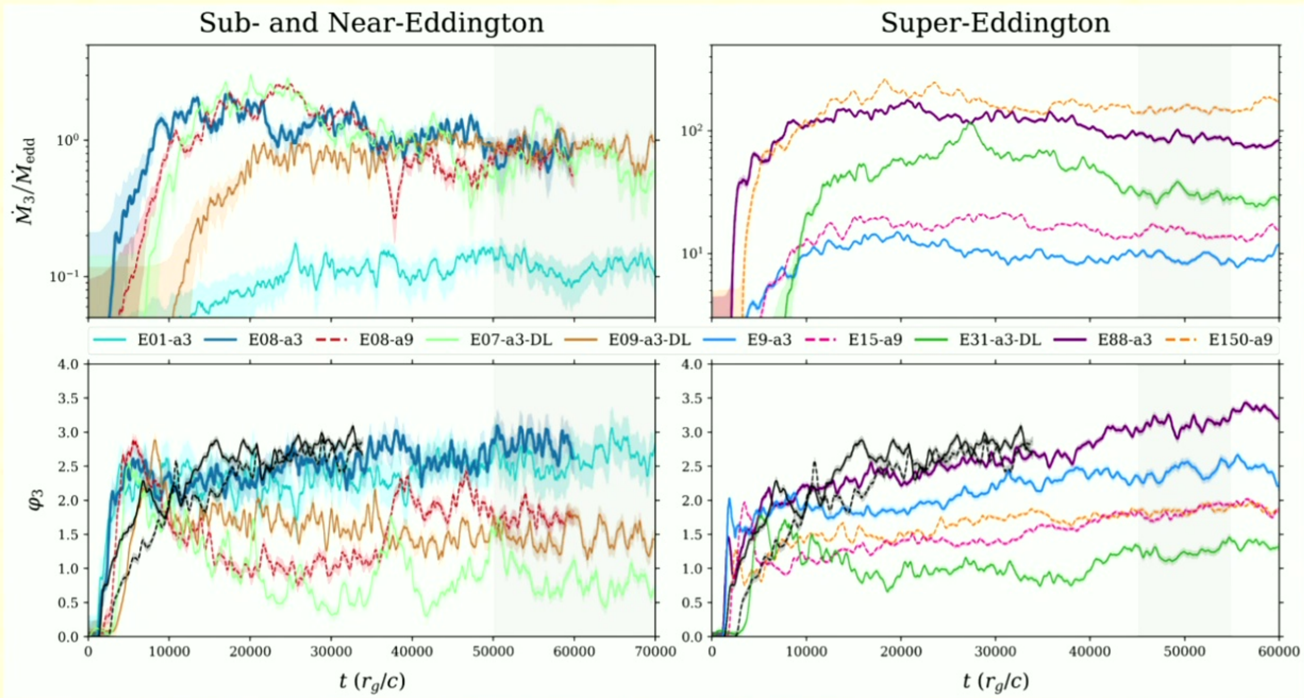


Zhang et al. (in prep, a)

Time Evolution

Mass accretion rate

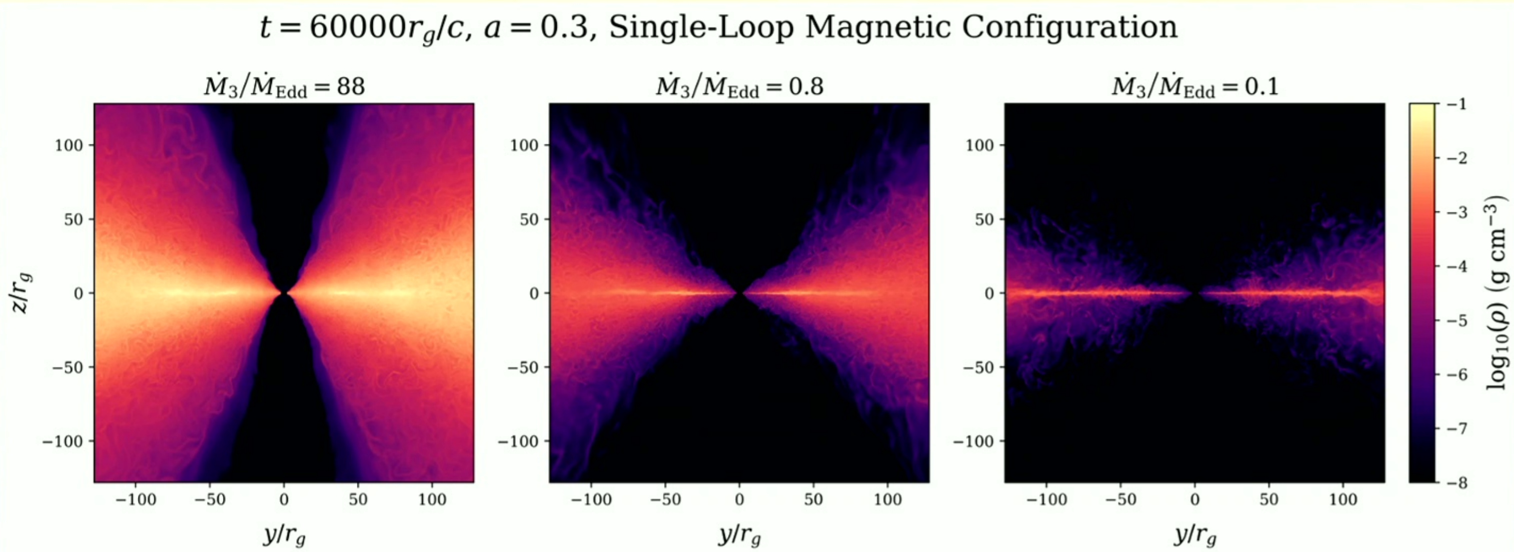
Magnetic flux on horizon



None of the models go MAD, even with single loop IC

Density structure with different accretion rates

A. **Super-Eddington:** radiation-supported thick disk + narrow funnel region
B. **Near-Eddington:** thermally supported thin disk + optically thick corona
C. **Sub-Eddington:** thermally supported thin disk + optically thin corona

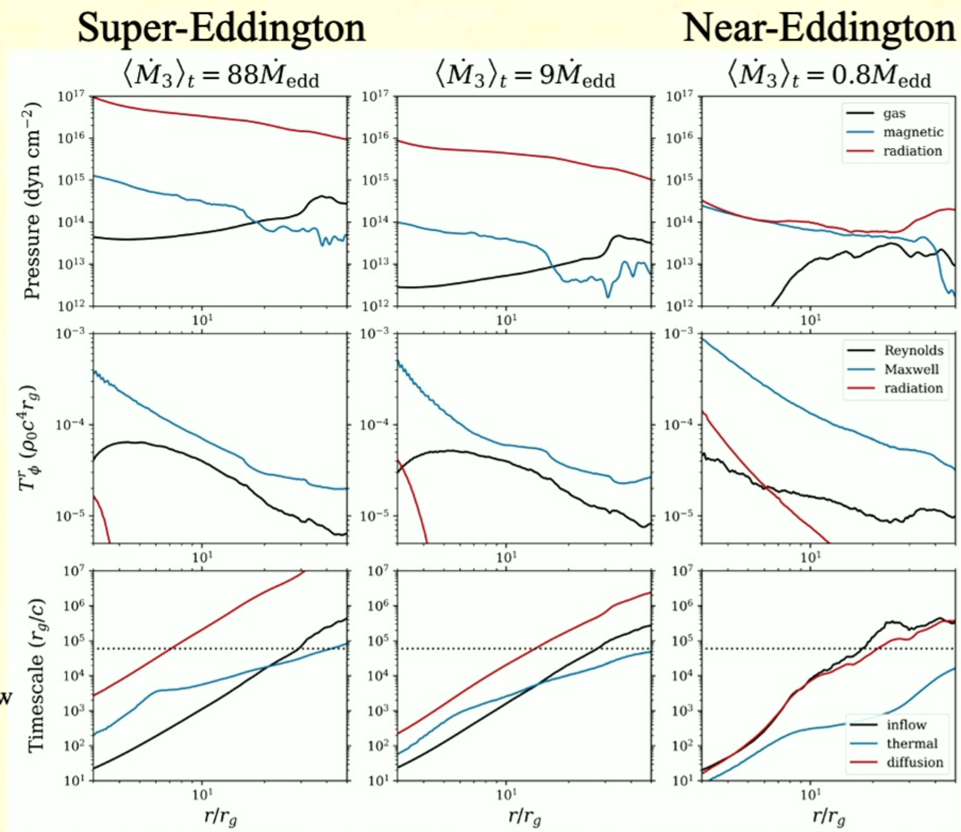


Zhang et al. (in prep, a)

Radial structure at different accretion rates

$P_{rad} >> P_{mag}$

$T_{thermal} >> T_{inflow}$



$P_{rad} \sim P_{mag}$

$T_{thermal} << T_{inflow}$

Also very important to compare to previous results using M1:

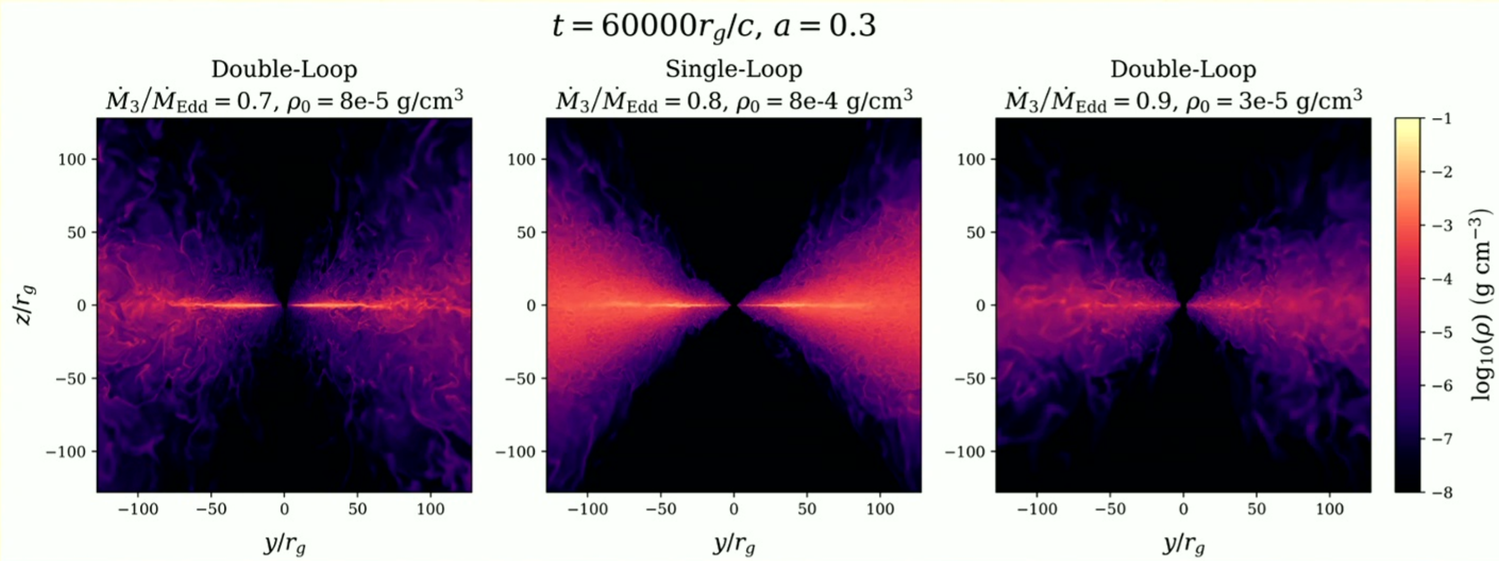
McKinney+ 2013; 2017, Sadowski+ 2013; 2017, Liska 2022; 2023

Structure with different initial magnetic fields

Distinct disk structure in the near-Eddington regime

A. **Single-loop** magnetic field: thicker disk, strong jet formation

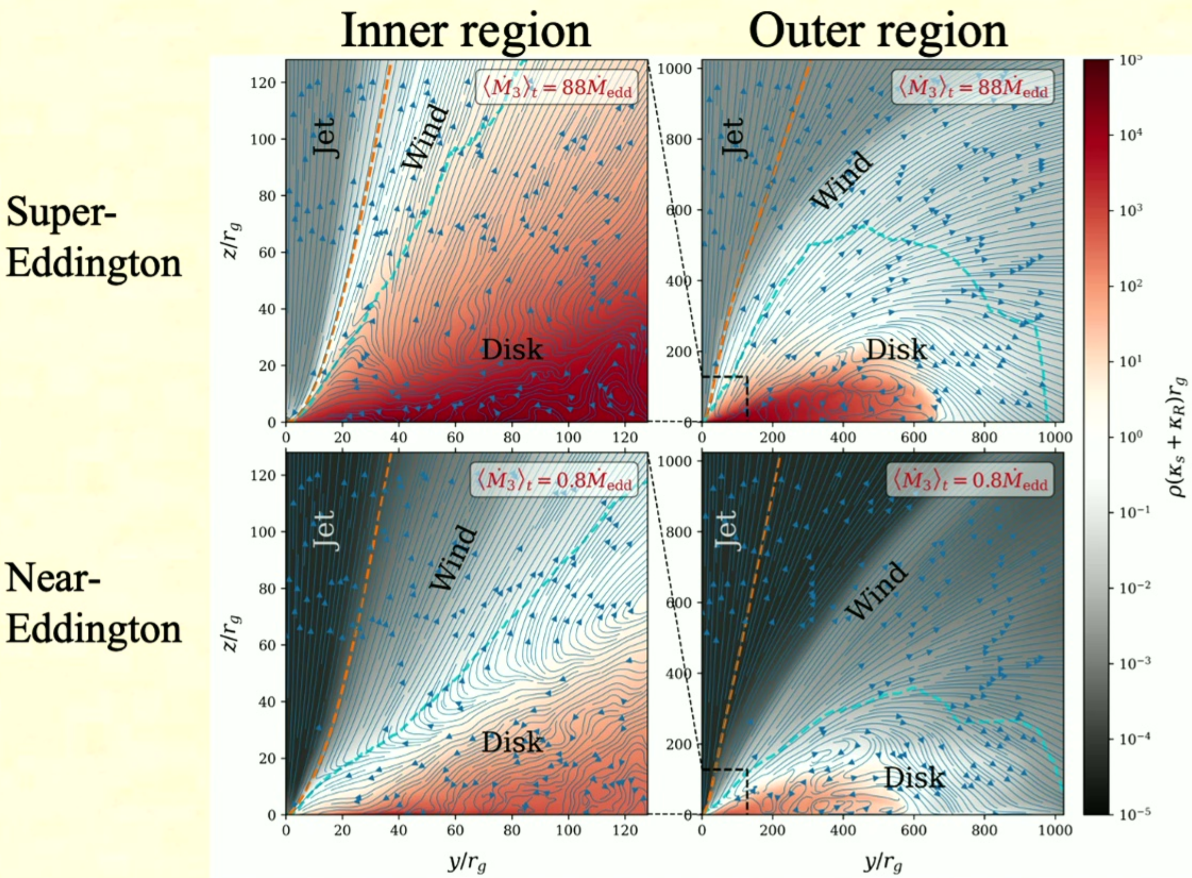
B. **Double-loop** magnetic field: thinner disk, weak or no jet formation



Zhang et al. (in prep, a)

Net magnetic flux in the disk may be an important parameter

Relativistic jets and powerful outflows



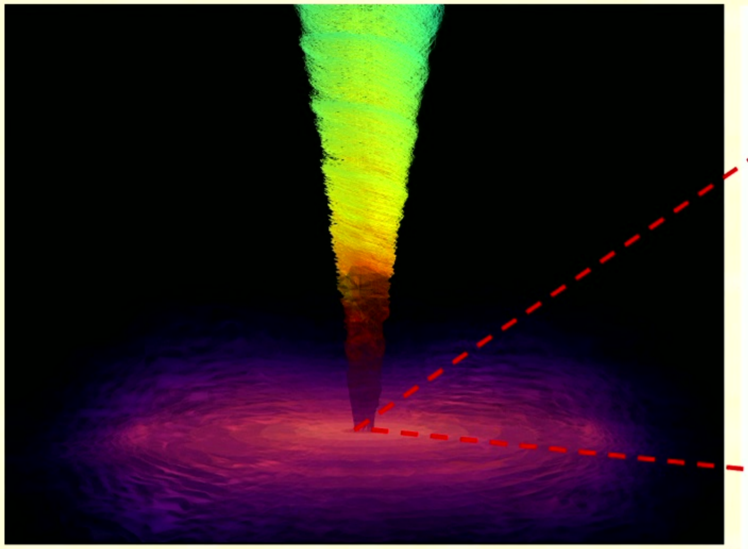
$\eta_{rad} \sim 0.53$
$\eta_{jet} \sim 0.64$
$\eta_{wind} \sim 0.32$

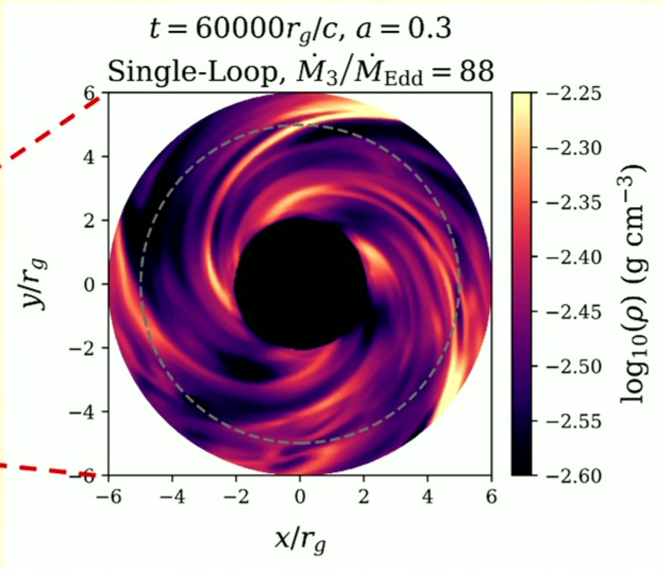
$\eta_{rad} \sim 3.87$
$\eta_{jet} \sim 0.61$
$\eta_{wind} \sim 2.35$

Color is optical depth per r_g

Plunging Region and Jet

With GR can extend the simulation domain to the horizon, which captures the physics in the jet and plunging region.





Comparing with Mummery and Balbus (2023) analytic solution for kinematics of inspiralling gas inside ISCO

Zhang et al. (in prep, b)

Currently we are focused on

- Post-processing to compute spectra, variability
- Sub-Eddington AGN models with *frequency-dependent* transport and opacities

But…

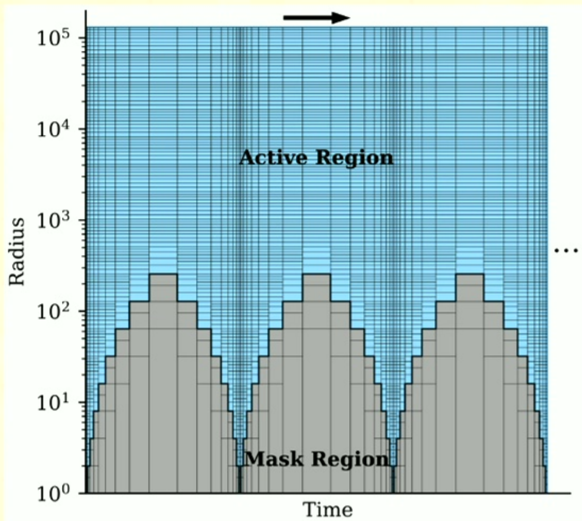
- What is the structure of black hole accretion flows on larger scales (Bondi radius)?
- *How are black holes fed?*

Modeling multi-scales with new algorithms

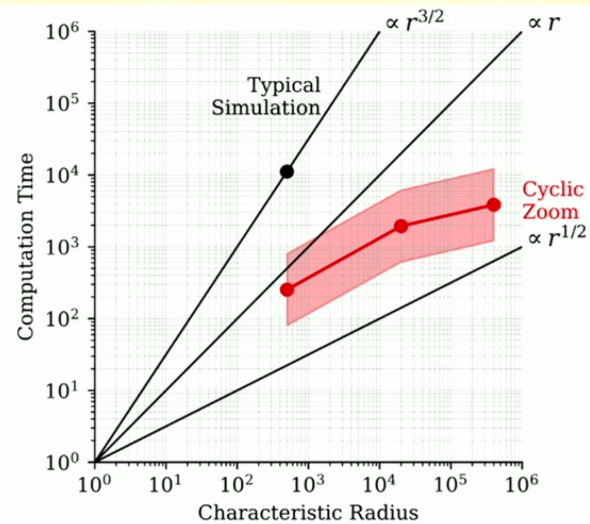
Work with Minghao Guo, Eliot Quataert

Even with exascale, modeling BH accretion over a vast range of scales on cosmological timescales is computationally prohibitive.

Based on an idea by Cho+2024, we have developed a **cyclic zoom-in/zoom-out** method. Coarsened solution in inner "mask" region used as subgrid model (Guo+ submitted)



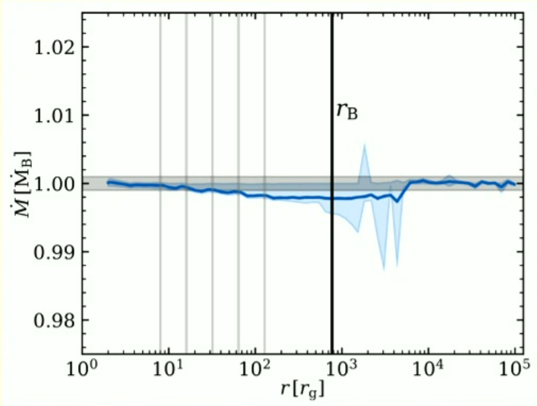
"Cyclic Zoom"



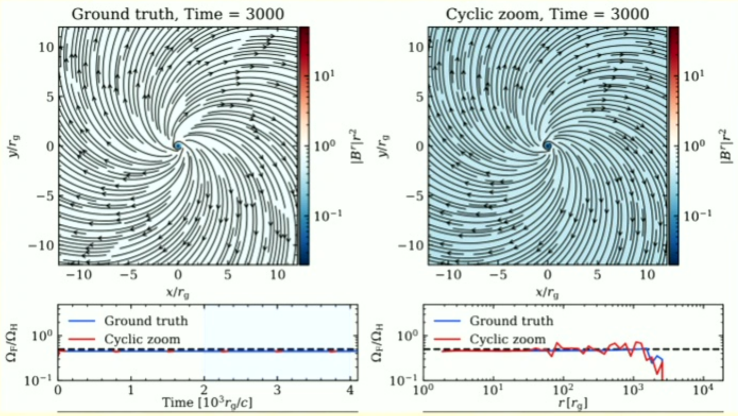
Speed-up for Bondi accretion

Cyclic-zoom reproduces “ground truth” remarkably well.

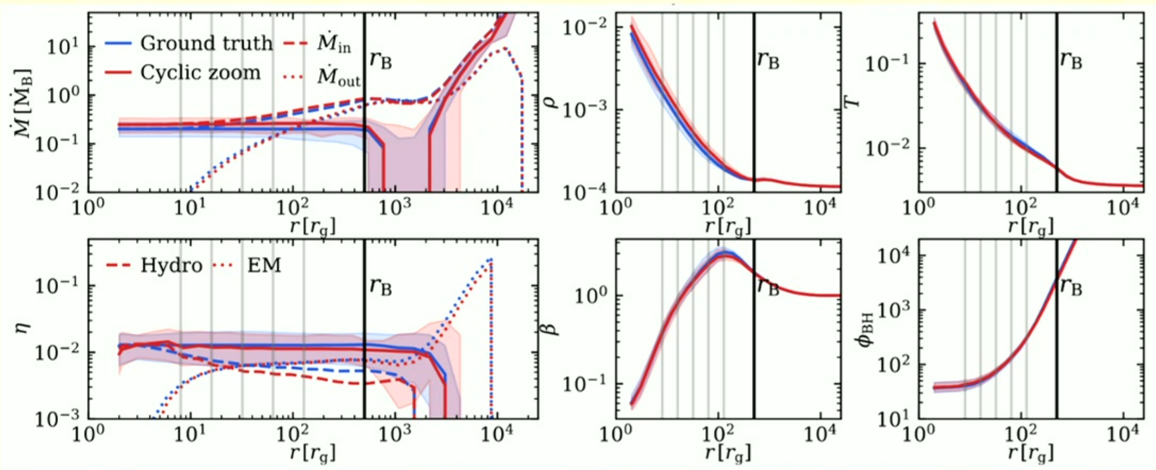
Hydro Bondi accretion



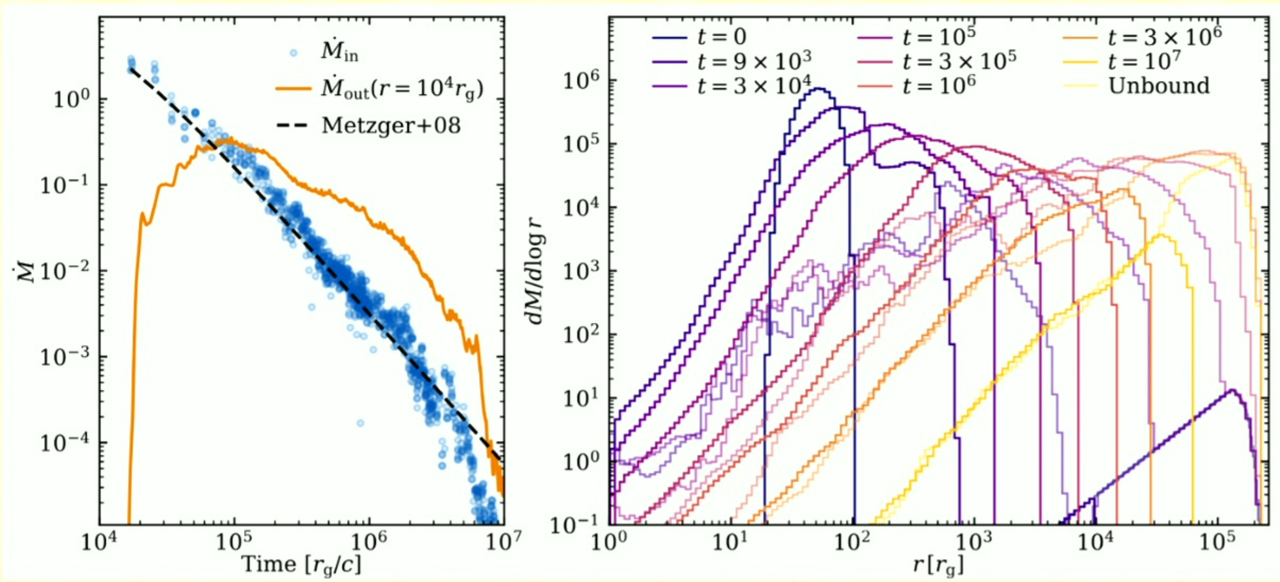
Split monopole threading rotating BH



MHD Bondi accretion



Cyclic zoom is already enabling study of new regimes. Example: long-term evolution of accretion torus



Good agreement with analytic models of Mummery & Balbus (2023)

Summary

New observations (EHT, JWST) and new (exascale) computing systems are pushing the frontiers of accretion disk modeling.

For **high-luminosity** (radiation-dominated) systems:

- New radiation-GRMHD models underway, extending previous work
- Models explore sub- to super-Eddington regimes
- Next: direct comparison of spectra, variability, etc.

New numerical methods allow bridging the enormous range of scales required to model feeding and feedback directly.