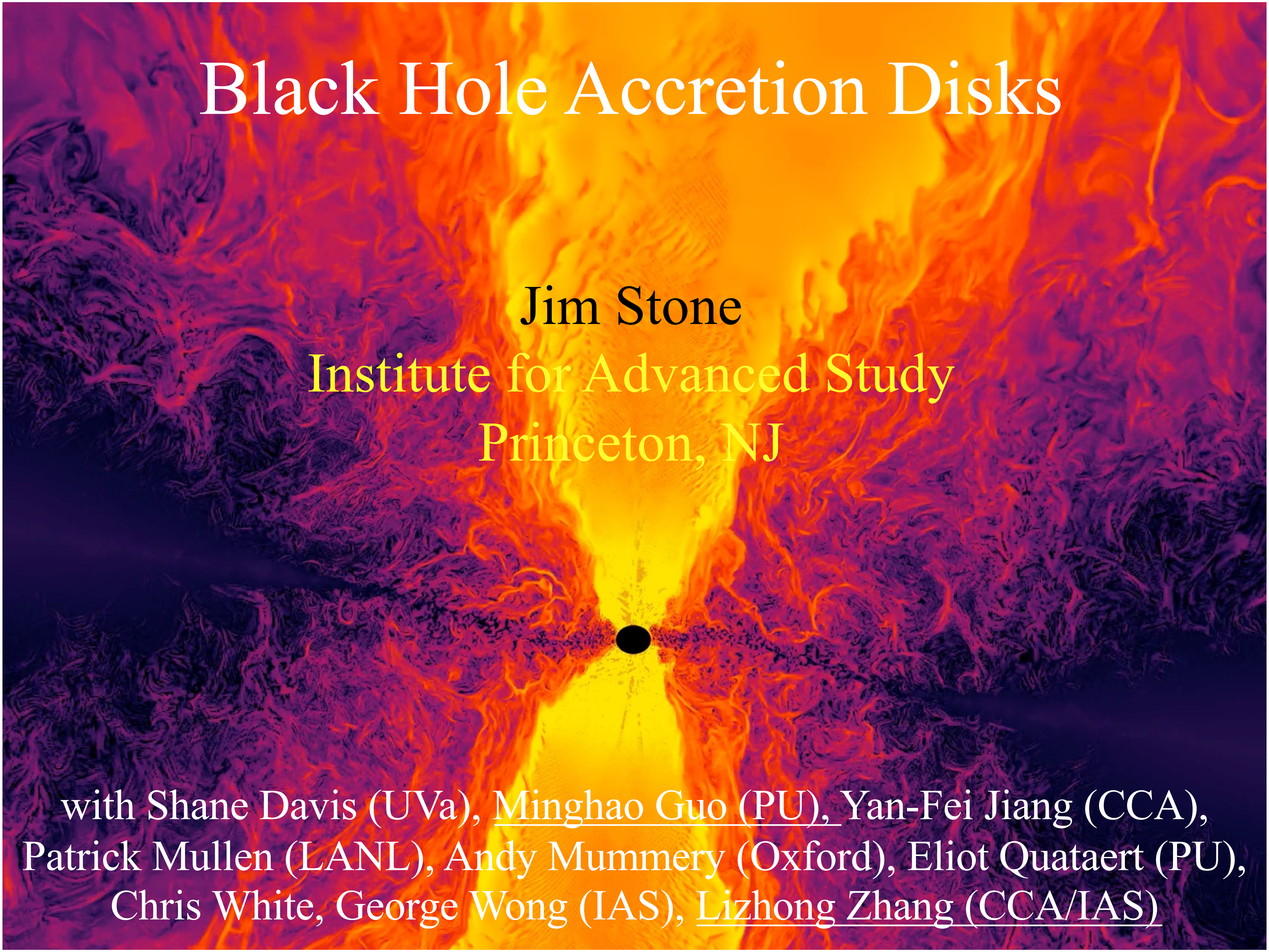

Black Hole Accretion Disks

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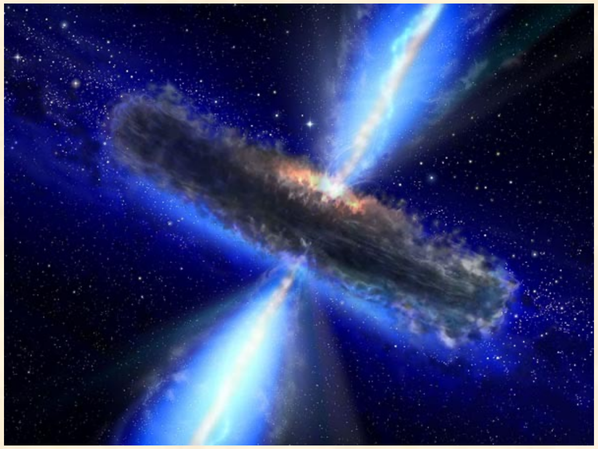
Outline

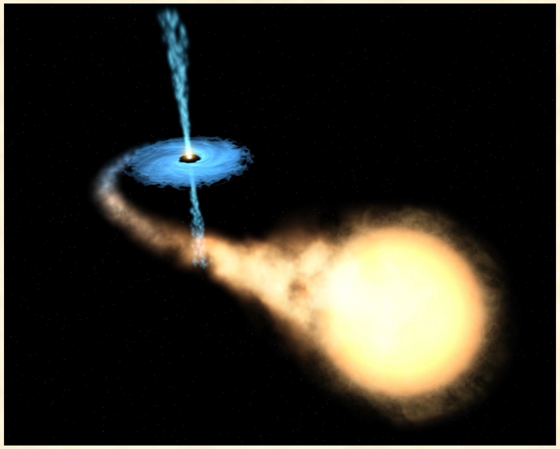
1. Motivation
2. Numerical methods
3. New global models
4. Cyclic zoom: long-term evolution

Motivation

- Accretion powers the most luminous known objects.



Quasars, AGN

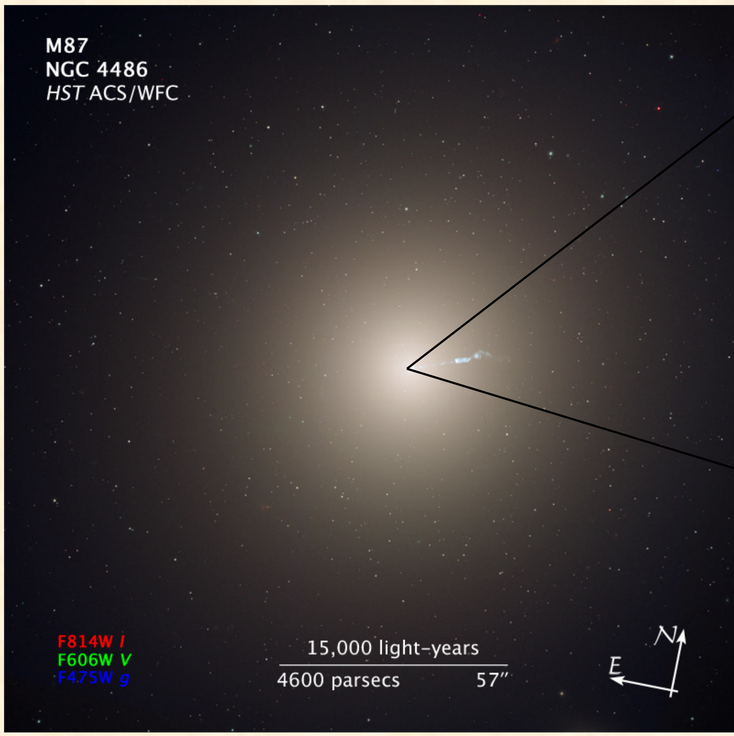


X-ray binaries

- Super-Eddington accretion may be important for the growth of black holes in the early universe.
- AGN feedback is important for galaxy formation.

First Image of BH Accretion

Event Horizon Telescope (EHT) has reported the first images of the supermassive BHs in M87 and Sgr A*.



EHT image of BH in center of M87 at radio (mm) wavelengths

Two modes of BH accretion

Low-luminosity

- Eddington ratio $L/L_{Edd} < 10^{-4}$
- Inefficient cooling
- Diffuse, nearly-collisionless plasma
- Kinetic effects important

Applicable to:

- EHT sources (Sgr A*, M87)
- X-ray binaries in low-hard state

Radiation-dominated

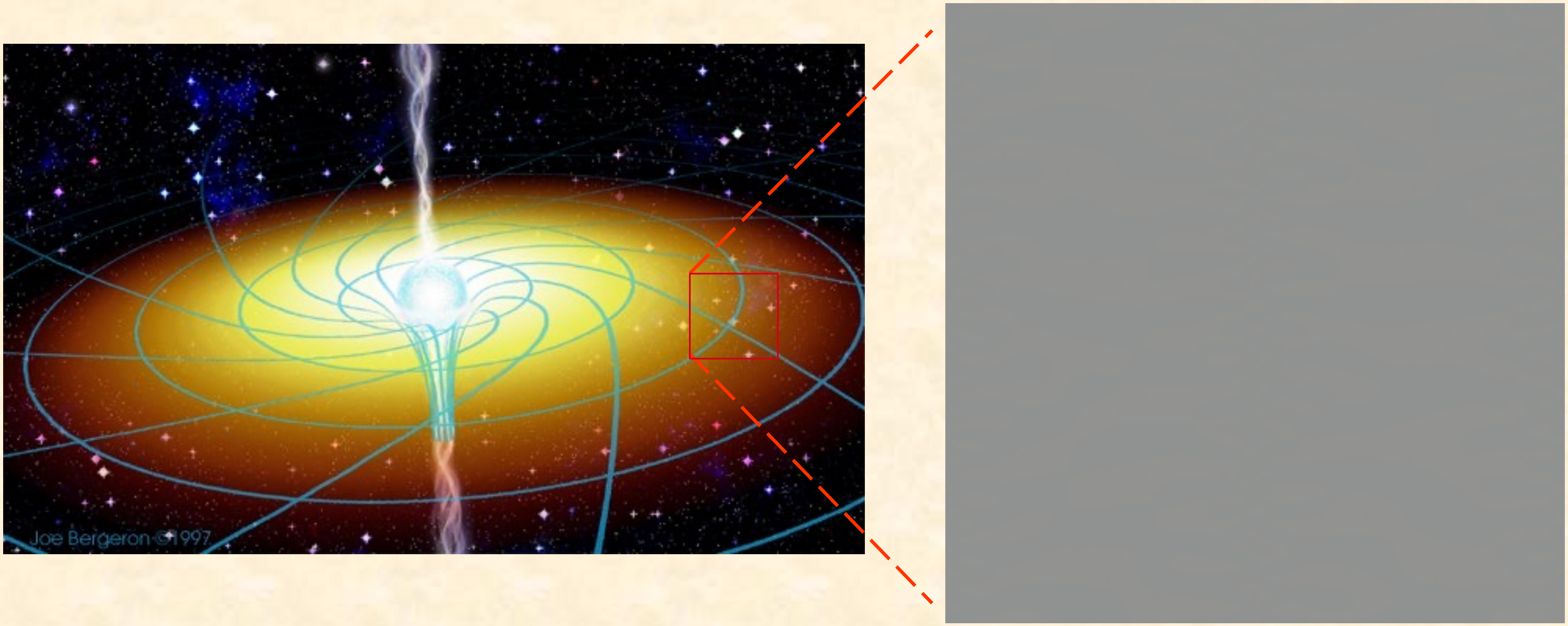
- Eddington ratio $L/L_{Edd} > 10^{-4}$
- Strong radiation and cooling
- Dense, collisional plasma

Applicable to:

- Quasars
- X-ray binaries in soft-high state
- Tidal disruption events

Magnetohydrodynamics is required

The magneto-rotational instability (MRI) drives accretion in black hole accretion flows.



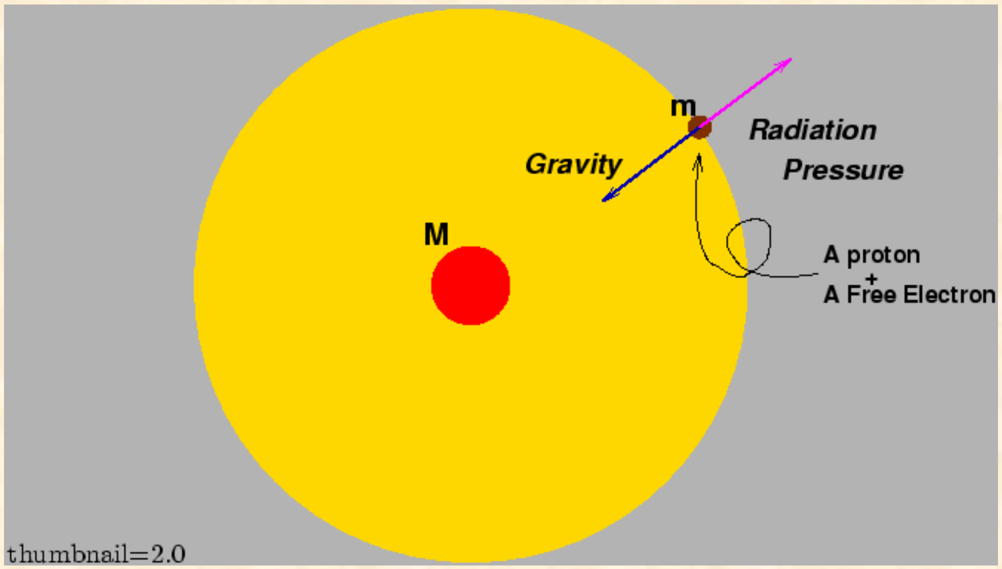
angular velocity fluctuations:
$\delta V_{\phi} = V_{\phi} - V_{Keplerian}$

Therefore MHD is essential

Eddington Limit

(Spherical) accretion only possible when:

outward force from radiation < inward pull of gravity



Forces balance when:

$$\frac{L\sigma_e}{4\pi r^2 c} = \frac{GMm_p}{r^2}$$

Eddington Luminosity: $L_{Edd} = \dfrac{4\pi GcMm_p}{\sigma_e}$

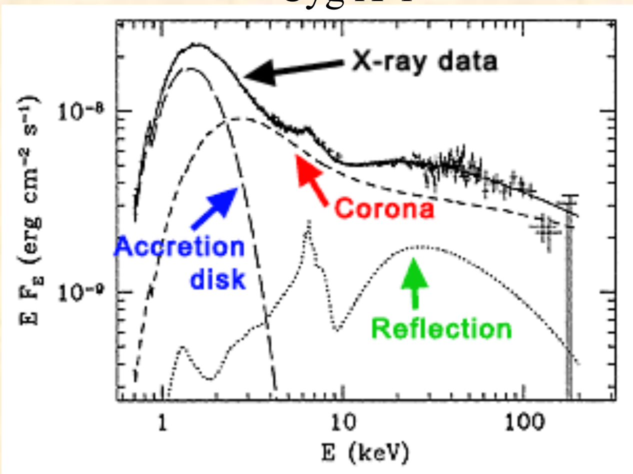
Therefore radiation is essential when $L \gtrsim L_{Edd}$

Some observationally motivated questions

- Some ULX sources are accreting neutron stars, L >> Ledd. In addition, Little Red Dots (LRDs) discovered by JWST are likely super-Eddington BH accretion.

  How does super-Eddington accretion occur?

Cyg X-1



- Spectra of sub-Eddington accretion disks ubiquitously show non-thermal (X-ray) emission, thought to be from a hot corona.

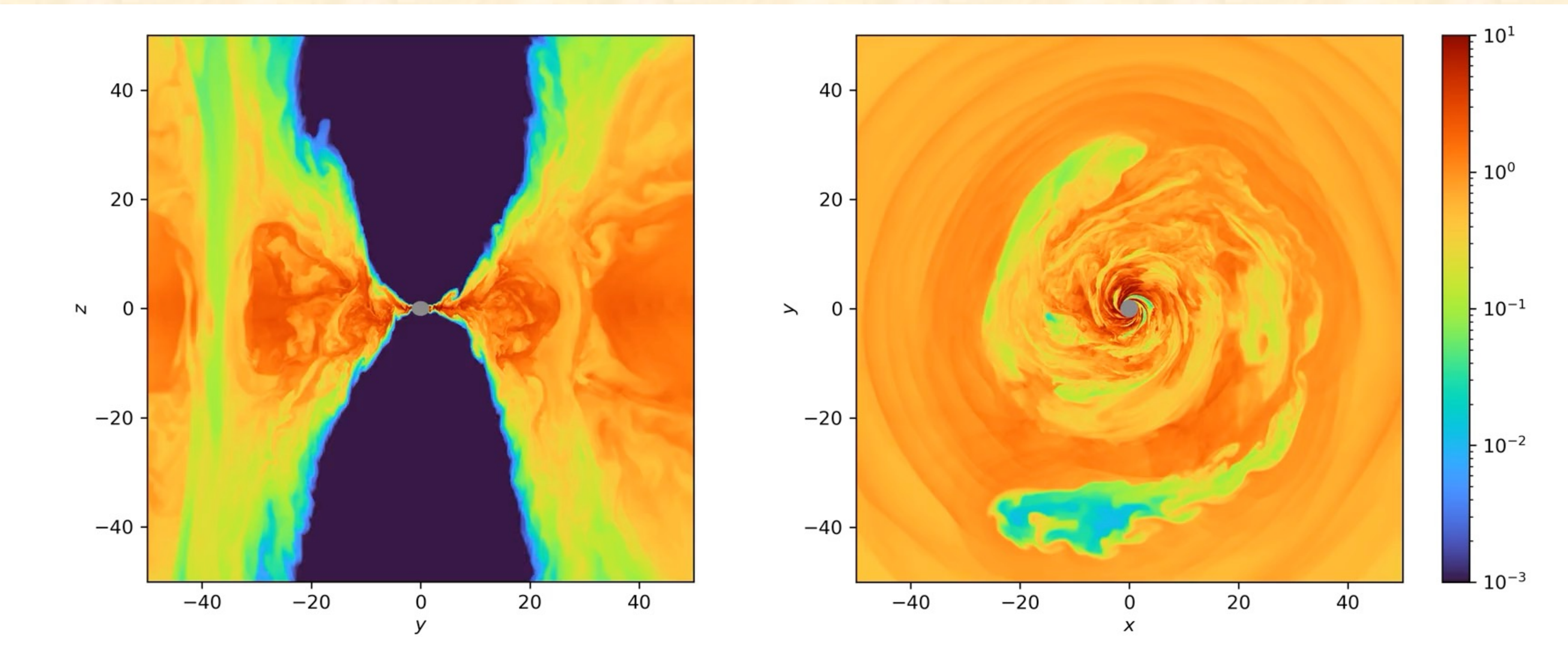
  How do accretion disks form coronae?

- Mass and spin of black holes are measured by spectral fitting, especially of Fe K-line profile, assuming α-disk model for continuum.

  Can we compute synthetic spectra and test continuum fitting models?

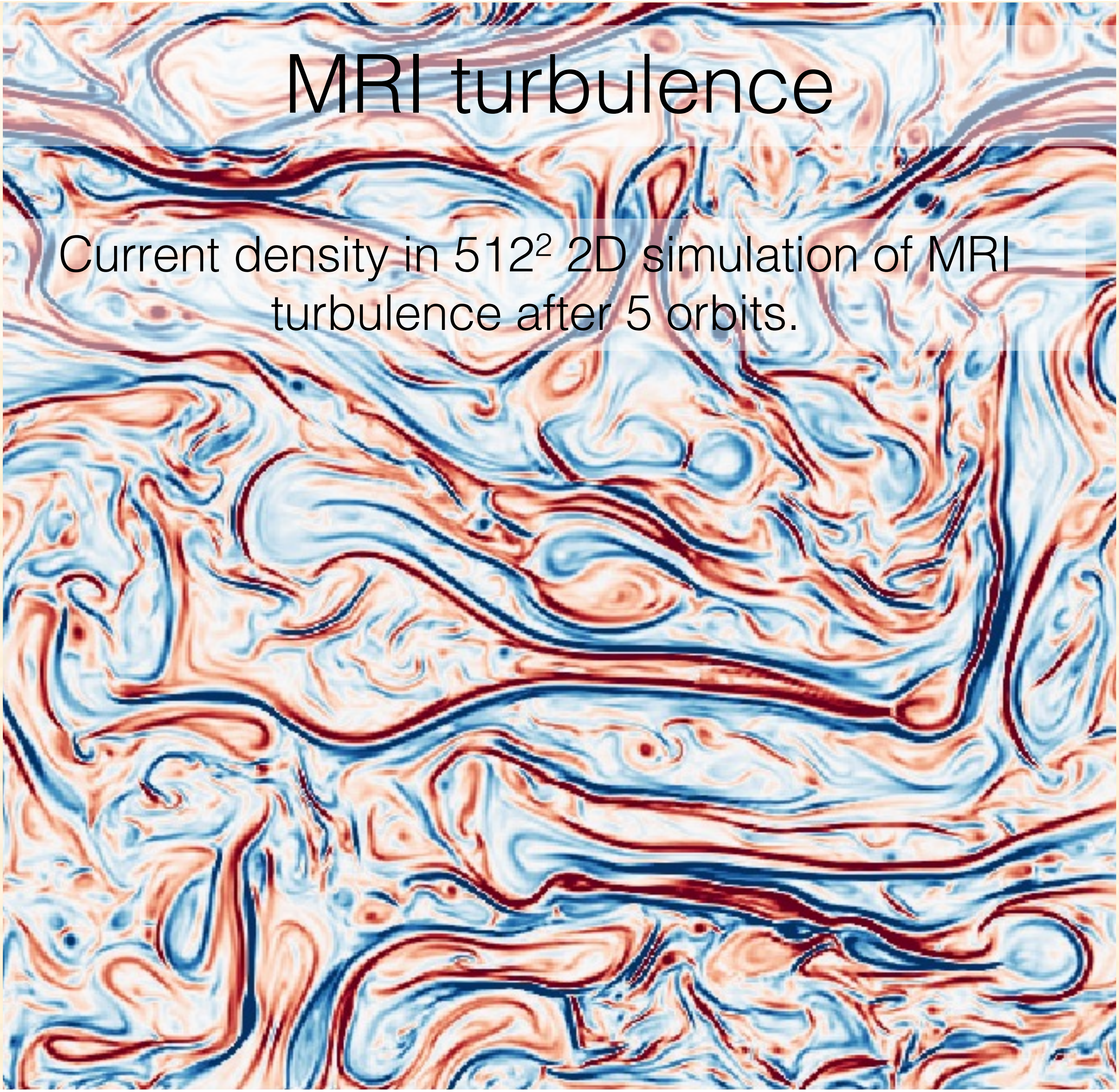
Numerical Methods: GR-MHD

- Numerical methods for solving the GR-MHD 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



MRI turbulence

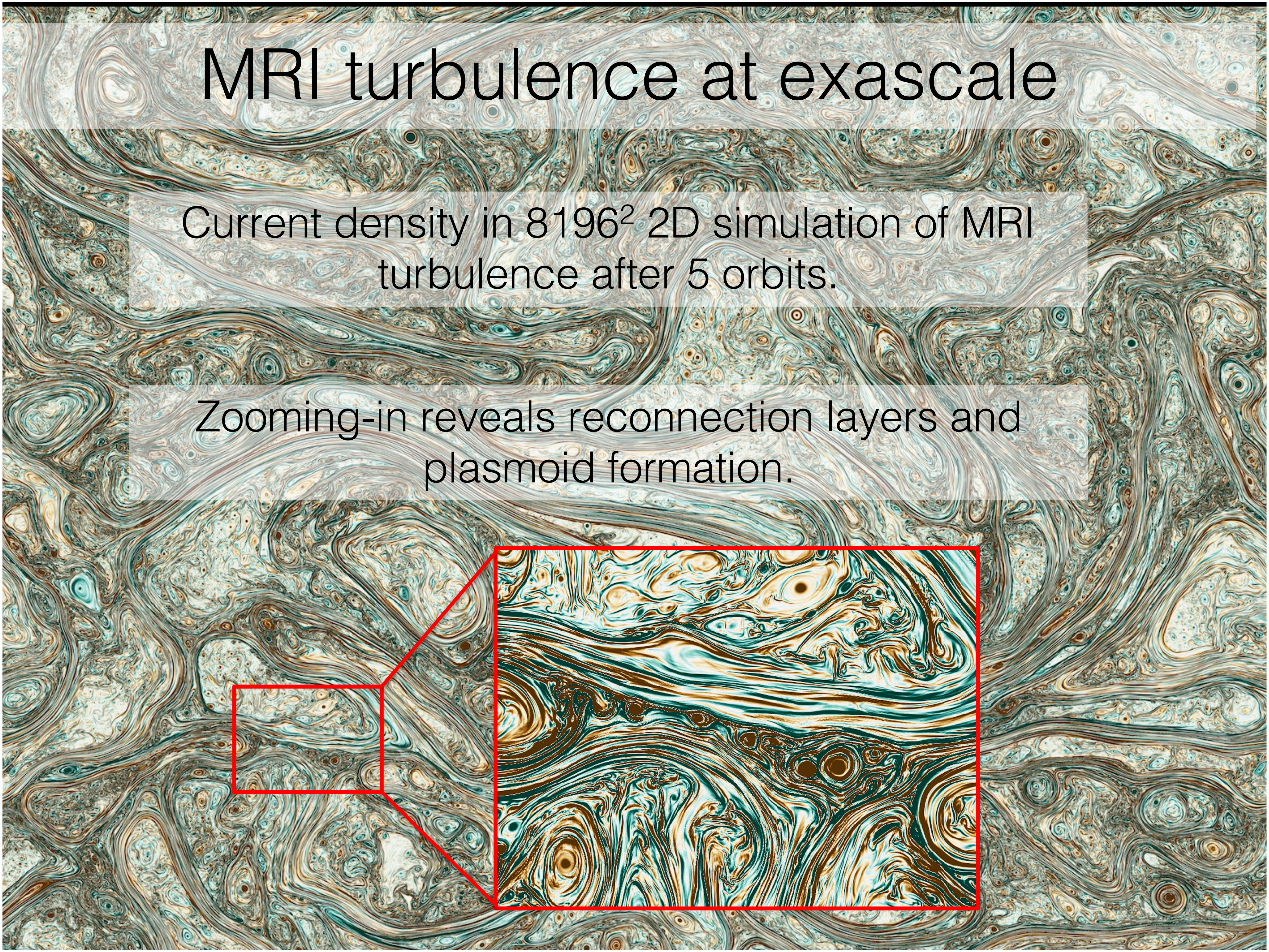
Current density in 512^2 2D simulation of MRI turbulence after 5 orbits.



MRI turbulence at exascale

Current density in 8196^2 2D simulation of MRI turbulence after 5 orbits.

Zooming-in reveals reconnection layers and plasmoid formation.



Exascale enables radiation physics

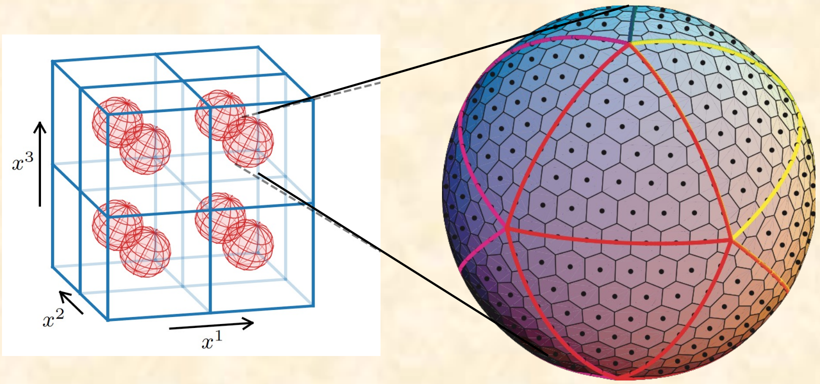
Black hole accretion flows with luminosities $L/L_{Edd} > 10^{-2}$ are in the radiation-dominated regime and must be modeled with radiation GRMHD.

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)

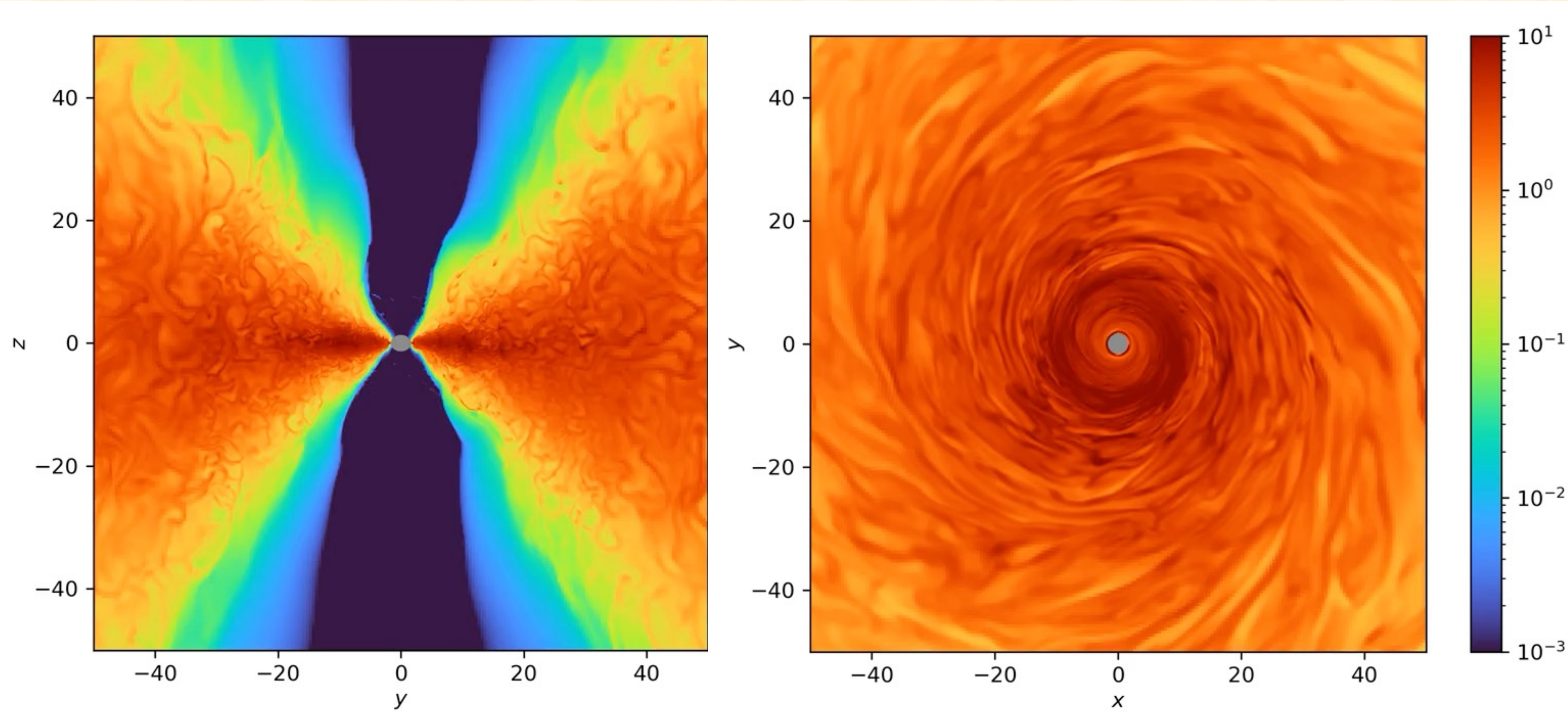
More uniform coverage of solid angle
Can be extended to adaptive angular meshes



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

Radiation-dominated black hole accretion

Example: starting from a torus, turbulent magnetized accretion flow at late times ($t > 10^4$ M) around a rapidly spinning black hole



Full transport solution, not diffusion or M1 approximation!

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 ×

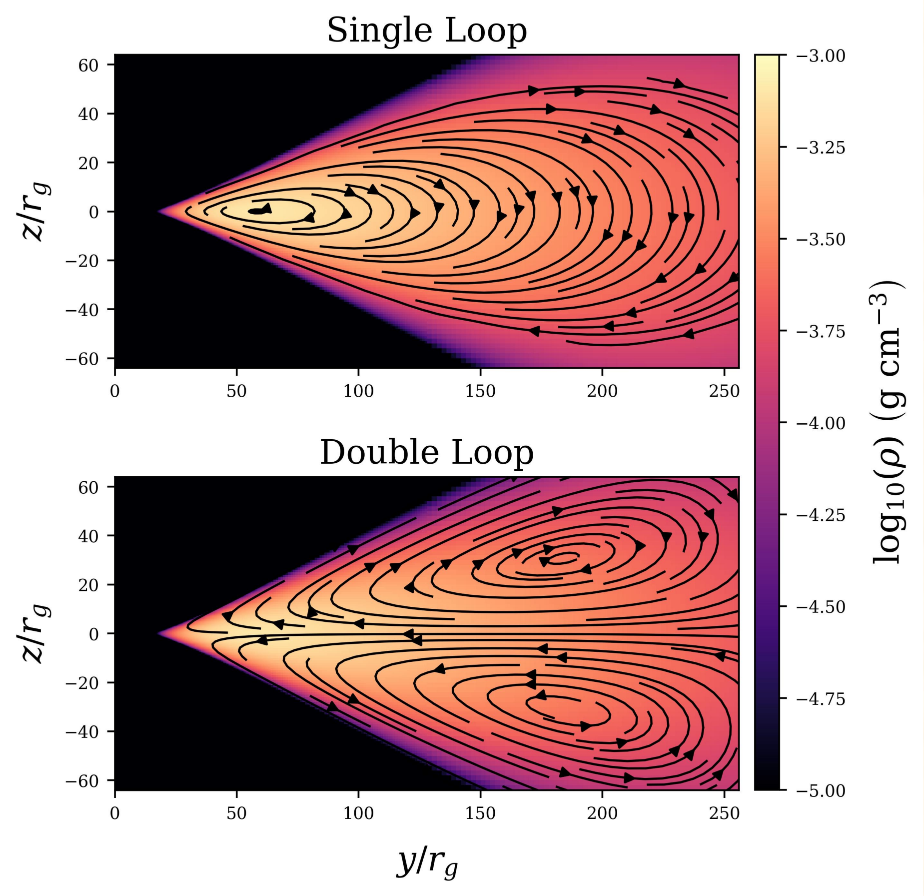
    Sub-Eddington: 0.1 ×, 0.01 ×

2. Black Hole Spin:

    a=0.3, a=0.9375

3. Magnetic Field Topology:

    Single-Loop, Double-Loop

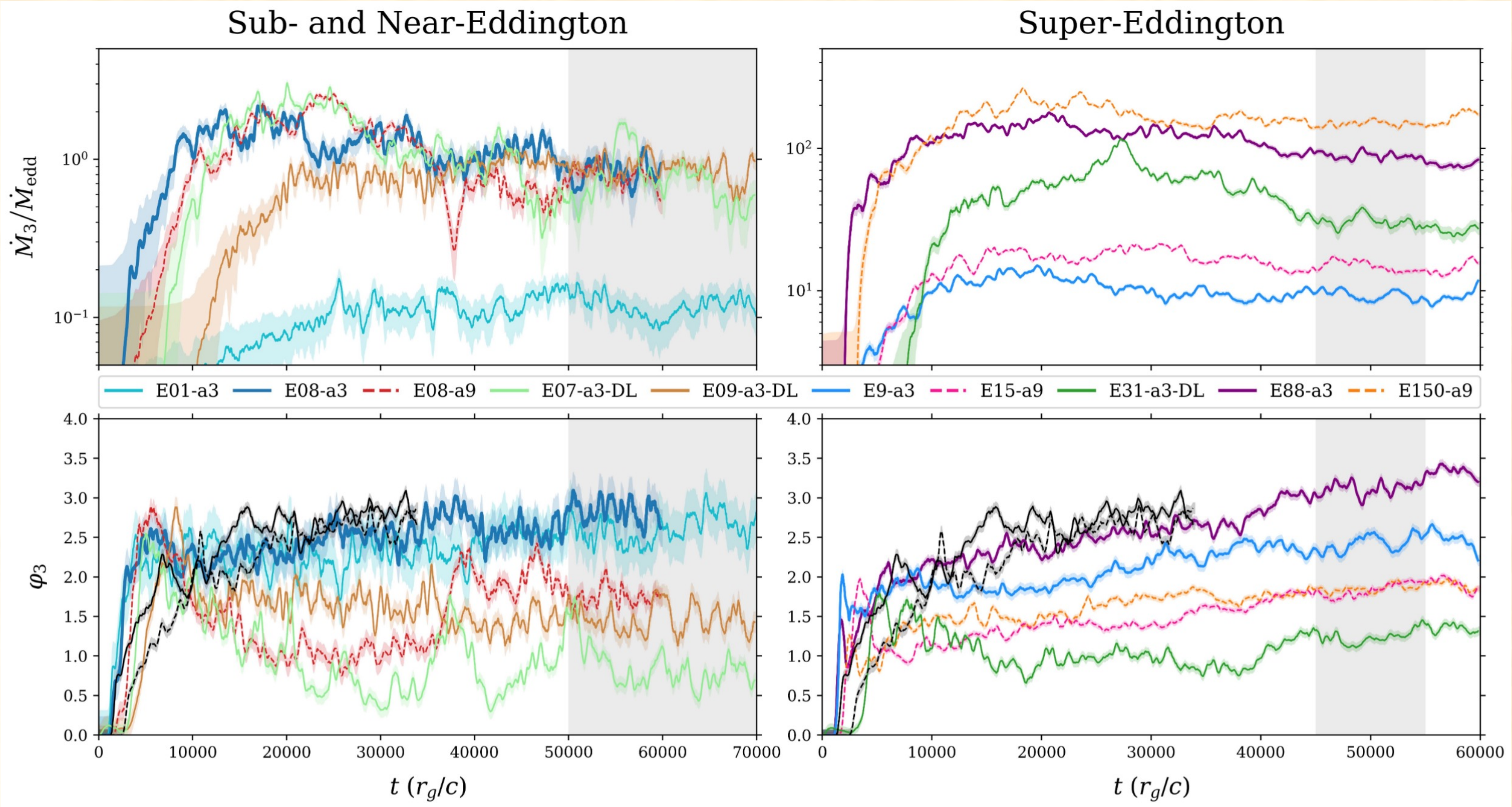


Zhang et al. (2025)

Time Evolution

Mass accretion rate

Magnetic flux on horizon



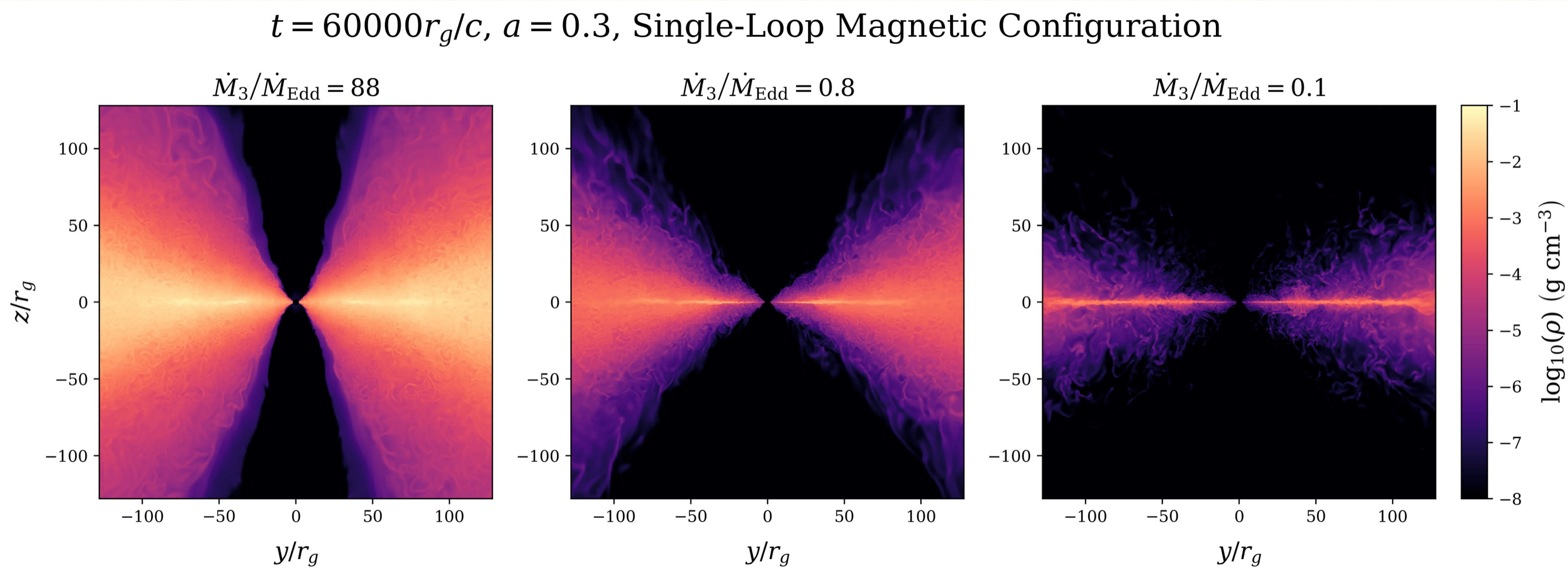
None of the models go MAD, even with single loop IC

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. (2025)

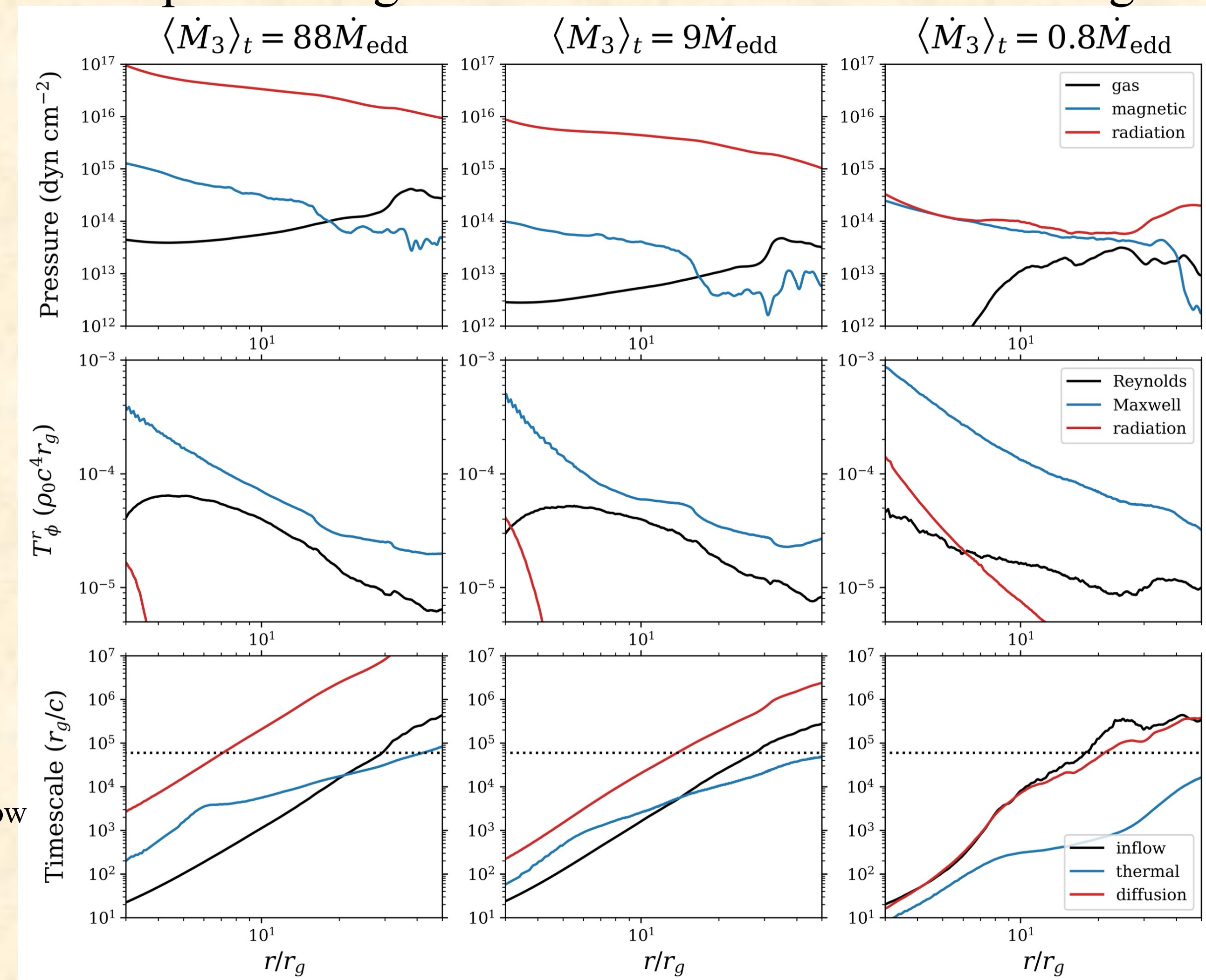
Radial structure at different accretion rates

Super-Eddington

Near-Eddington

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

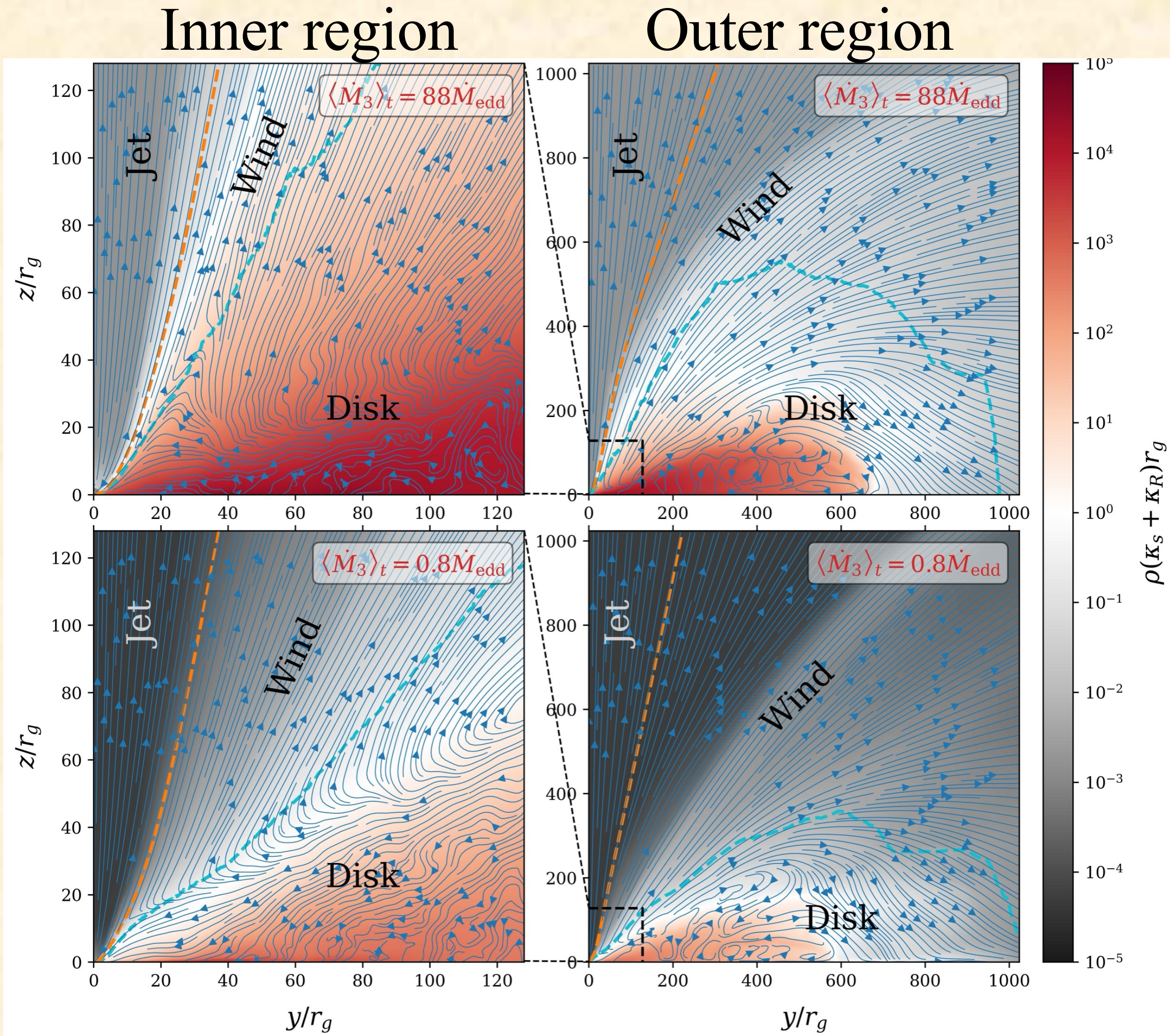
$P_{rad} \sim P_{mag}$



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

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

Relativistic jets and powerful outflows



Super-Eddington

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

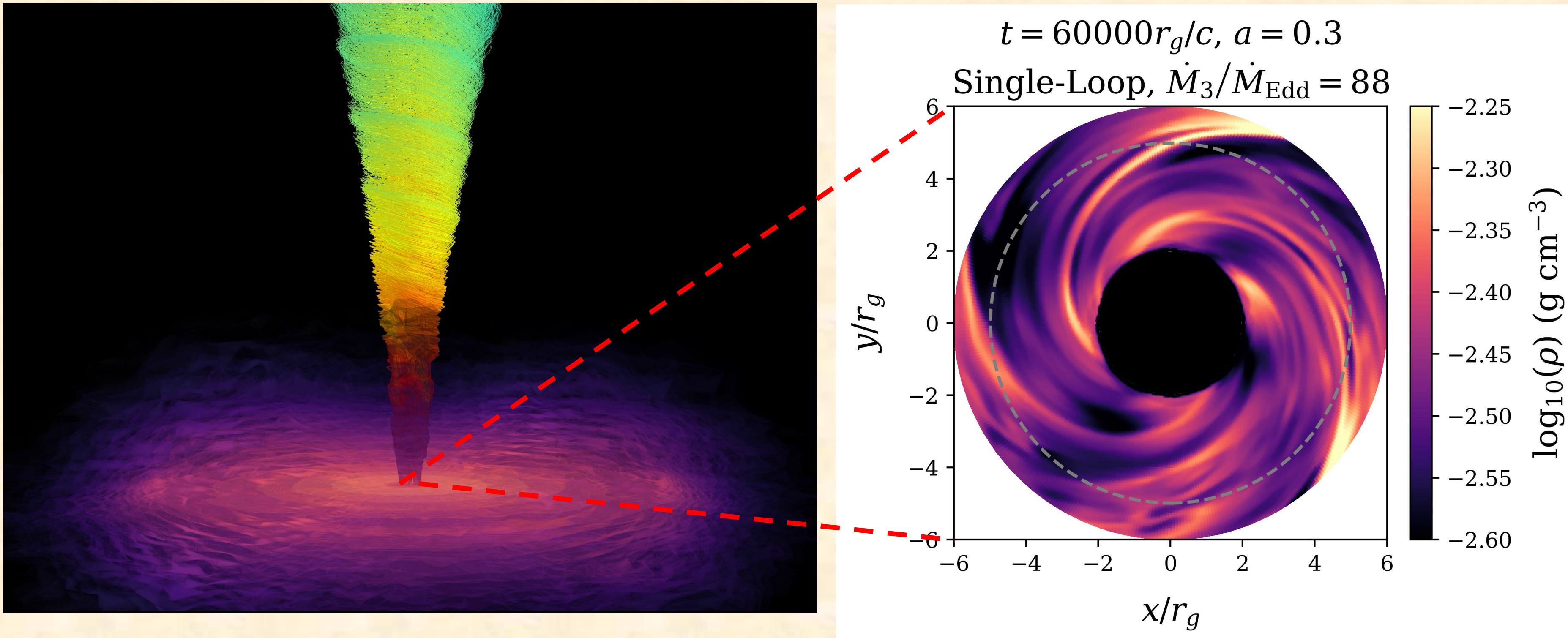
Near-Eddington

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

Color is optical depth per r_g

Plunging Region and Jet

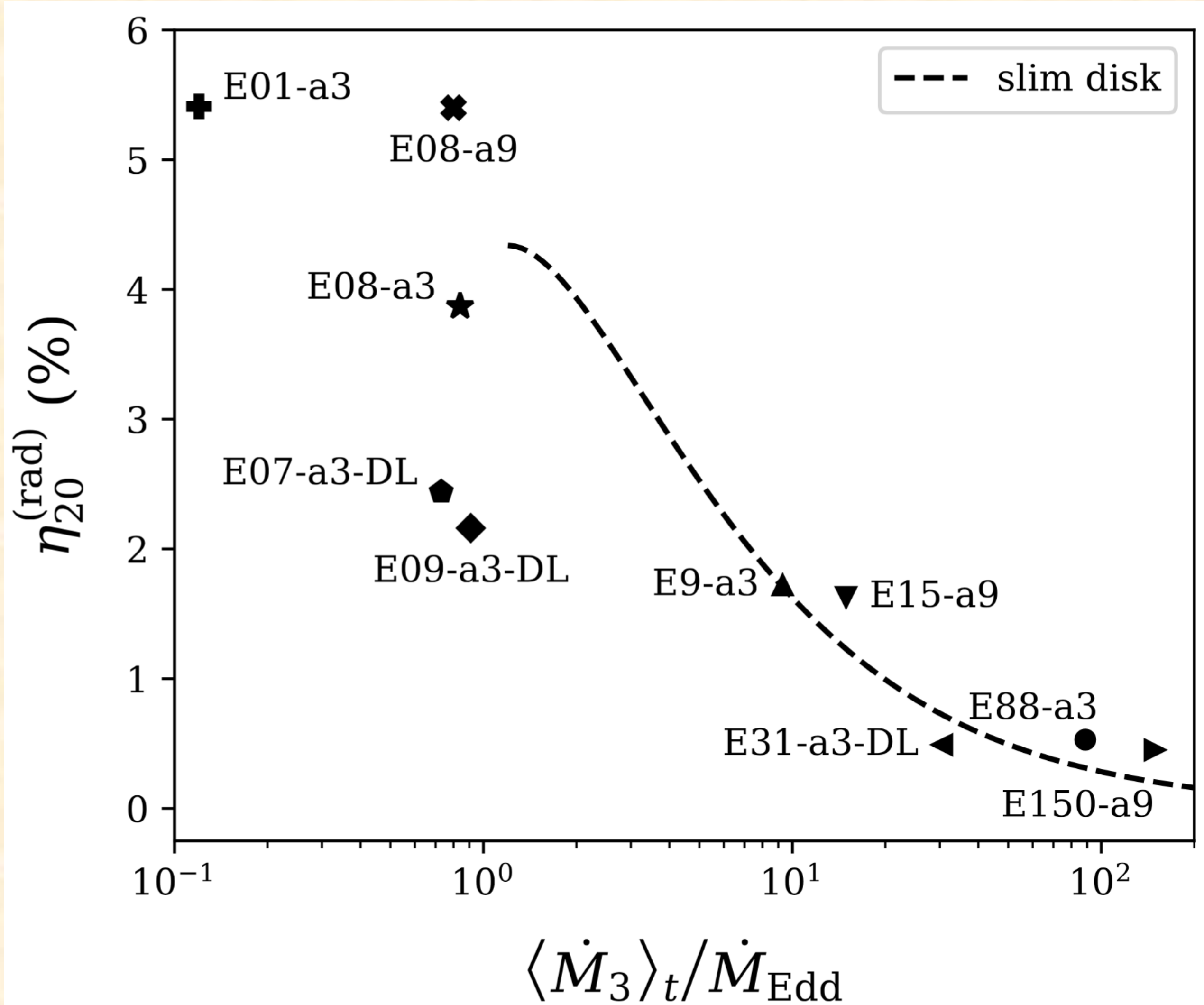
With GR can extend the simulation domain to the horizon, which captures the physics in the jet and plunging region.



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

Zhang et al. (2025b)

Radiative Efficiency

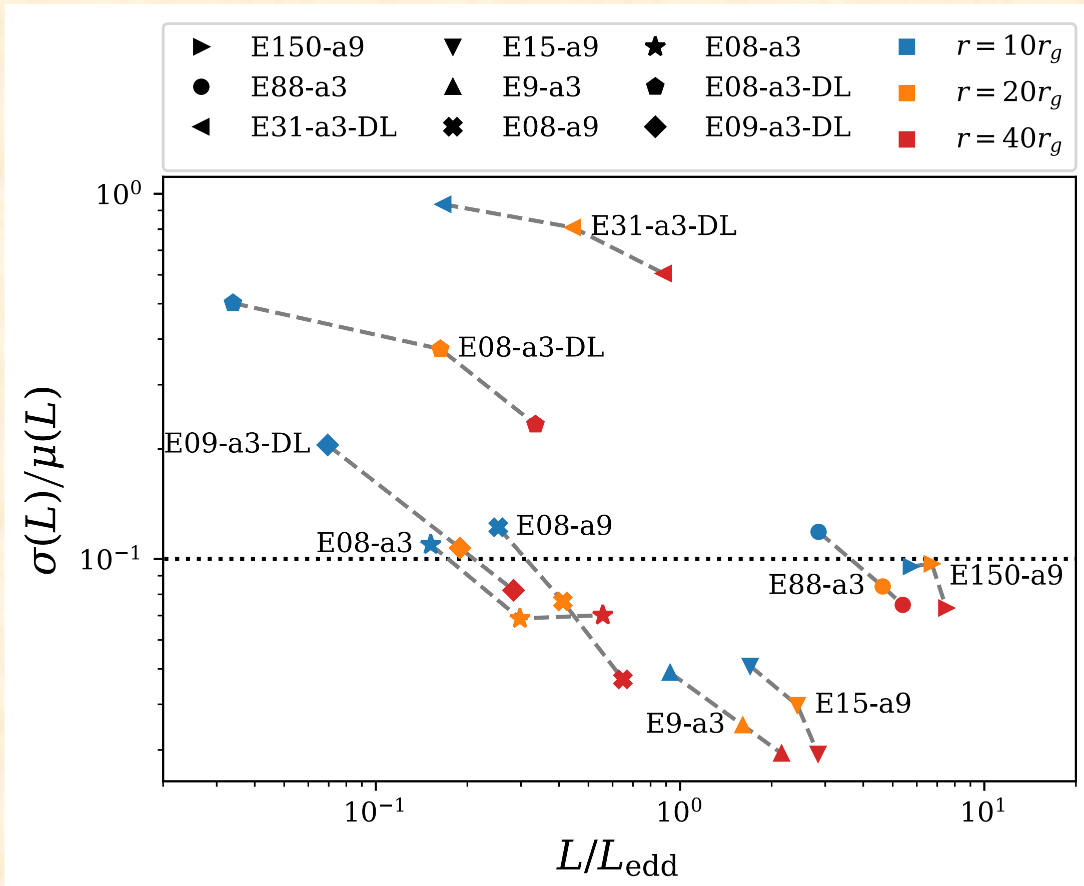


Super-Eddington accretion has very low radiative efficiency (Poutanen 2007)

Some observational consequences

- Highly super-Eddington accretion is not highly luminous
- Variability lowest for models with net vertical flux

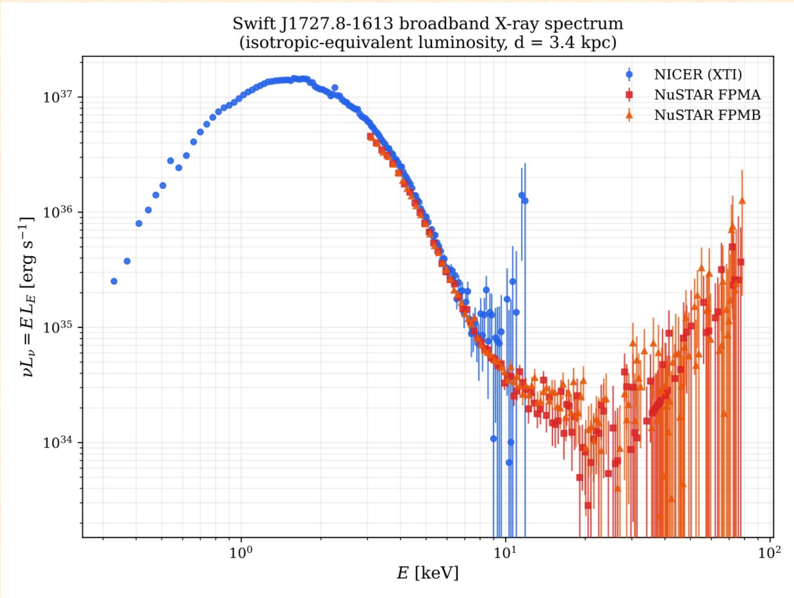
Percentage variability



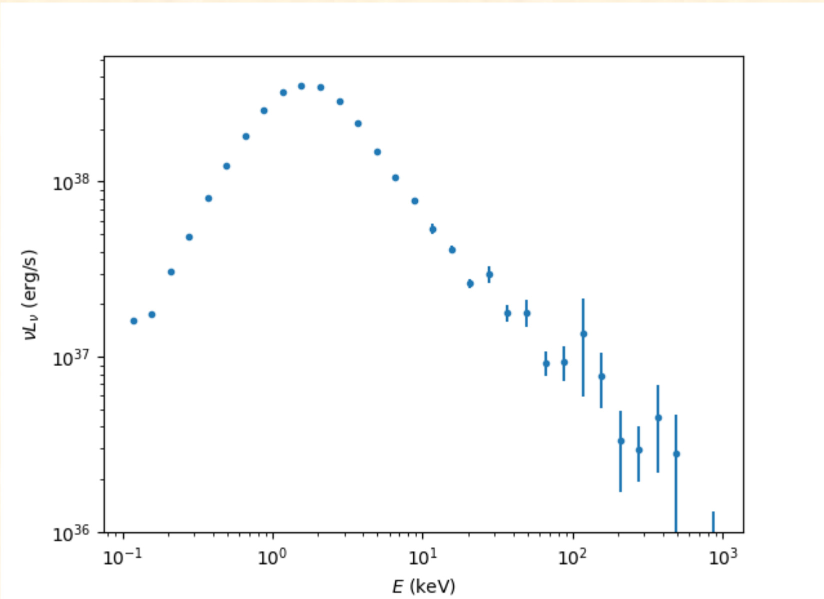
Computing spectra

Uses Monte-Carlo methods to post-process models including Compton and free-free scattering and absorption (work led by Shane Davis)

Typical X-ray spectra



Typical X-ray spectra of sub-Eddington model

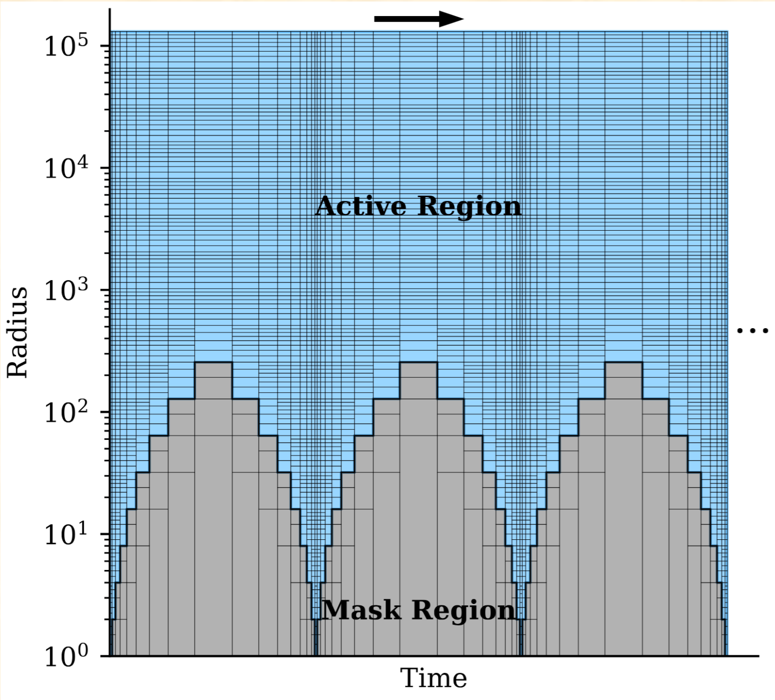


Future Challenge: multi-scale physics

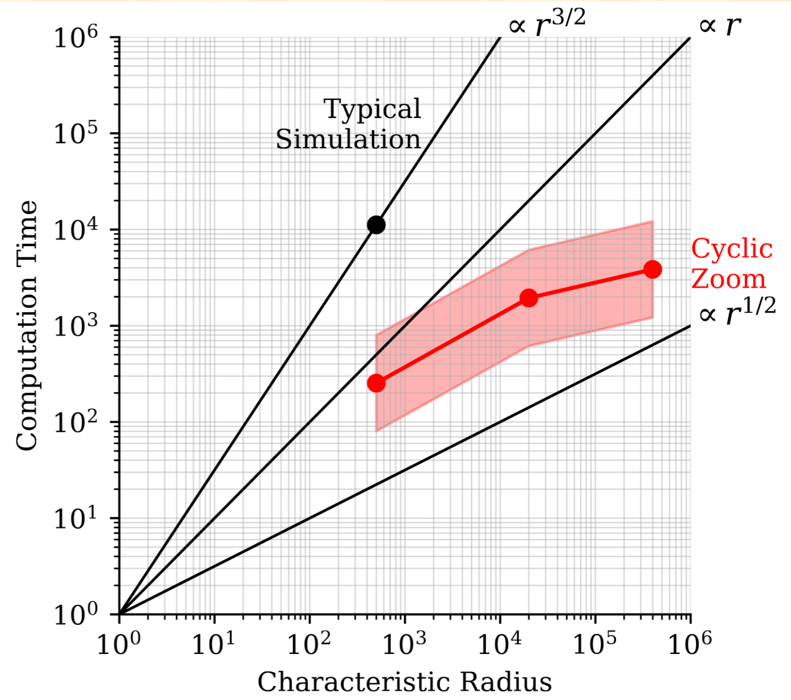
Work with Minghao Guo, Eliot Quataert, Volker Springel

Even with exascale, modeling BH accretion over a vast range of scales on ***evolutionary 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+ 2025)



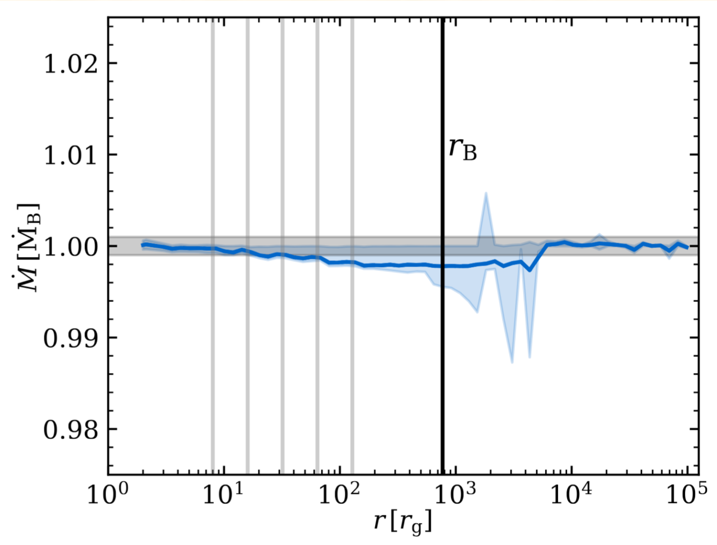
"Cyclic Zoom"



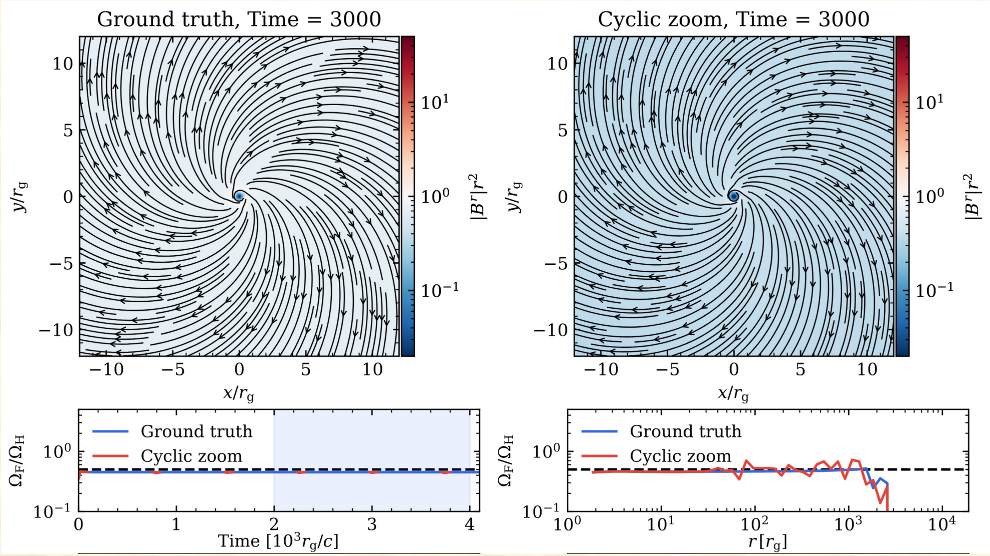
Speed-up for Bondi accretion

Cyclic-zoom reproduces "ground truth" remarkably well.

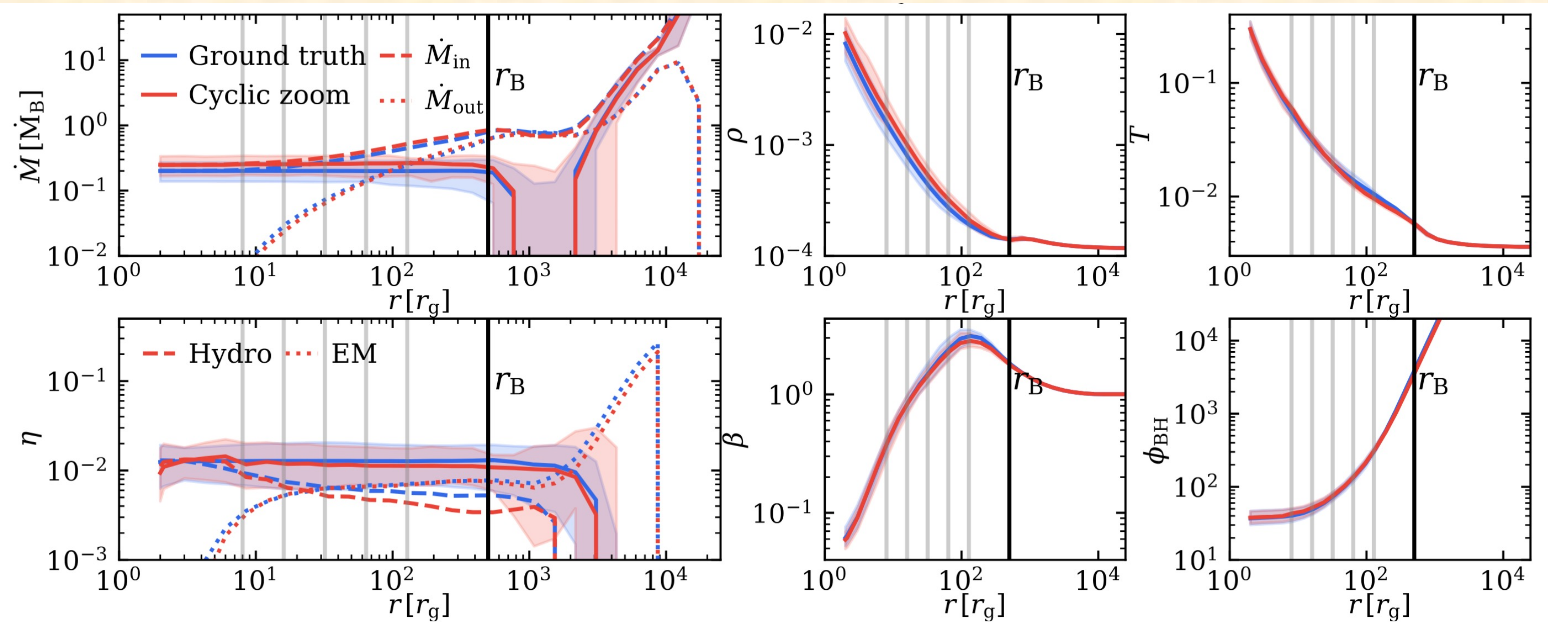
Hydro Bondi accretion



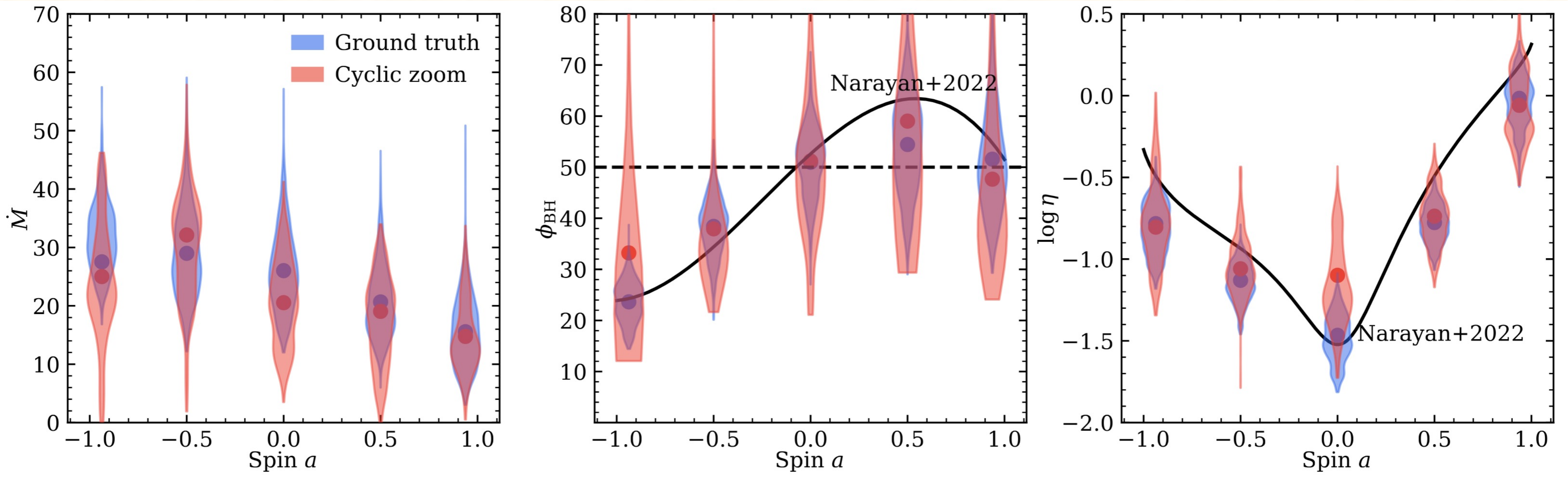
Split monopole threading rotating BH



MHD Bondi accretion

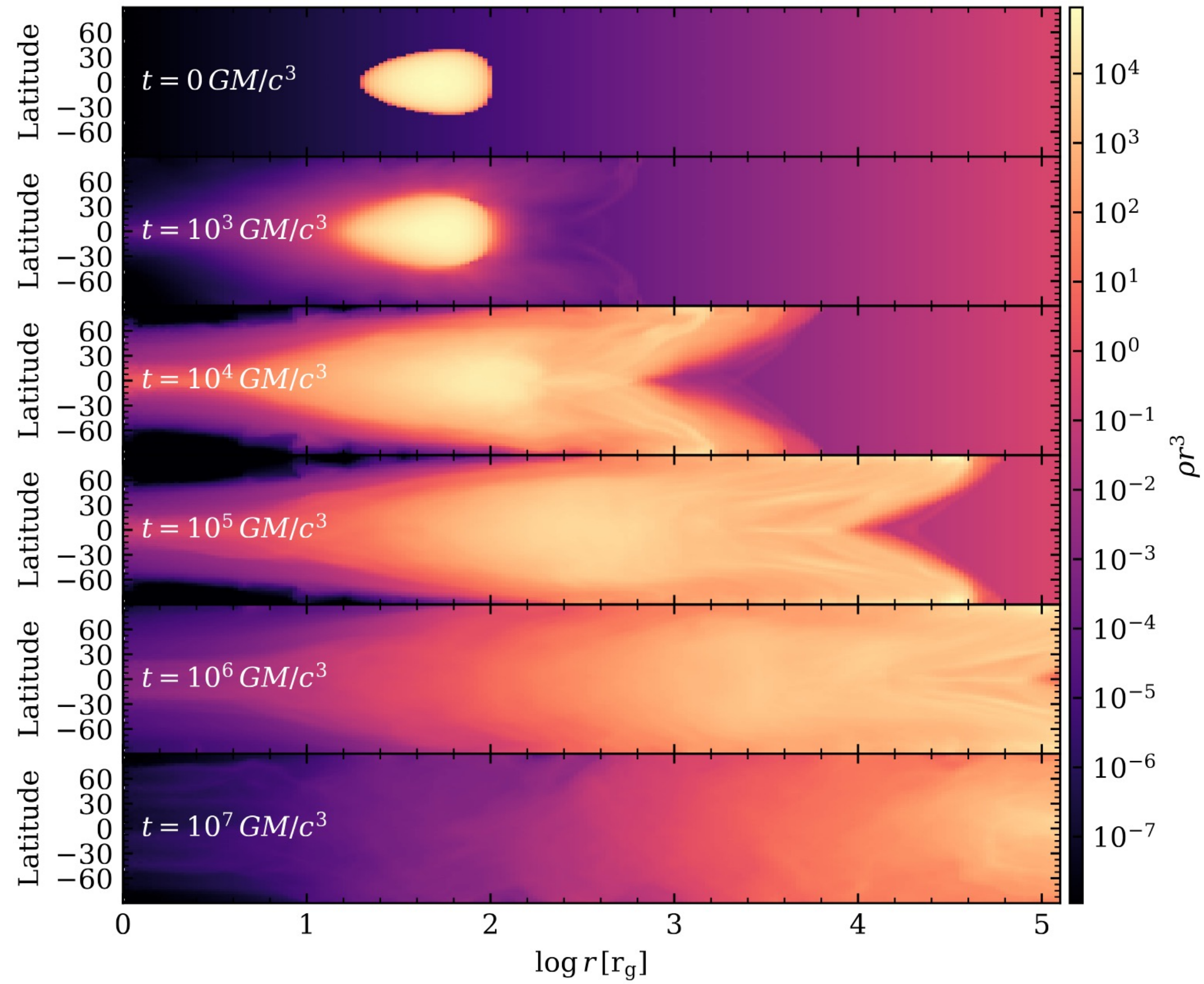


Captures evolution of accretion disk in GRMHD



Reproduces accretion rate, flux at horizon, efficiency for different spins

Cyclic zoom is enabling study of long-term evolution of accretion torus



Density evolution

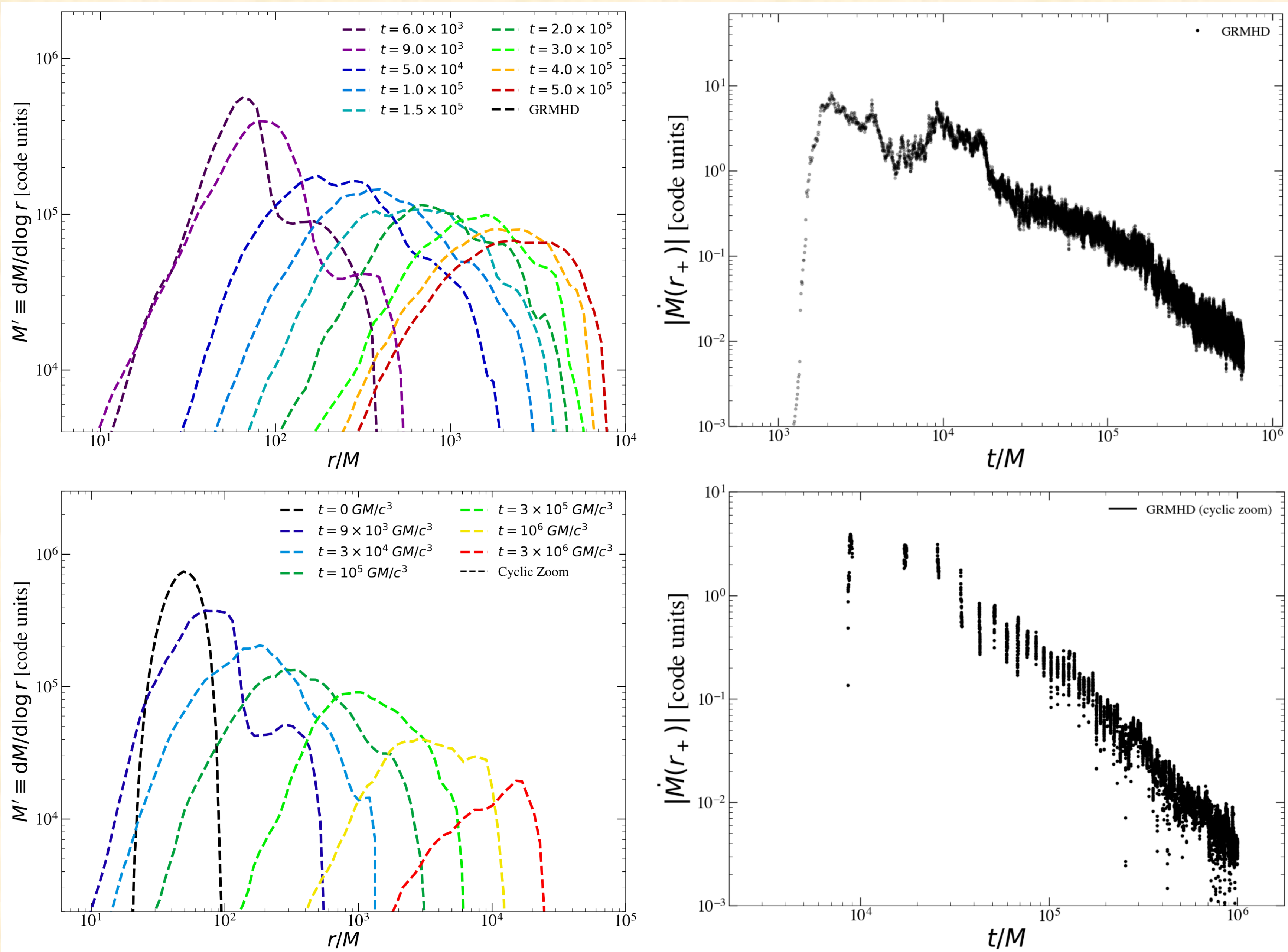
Mummery+ 2026

Mass profile

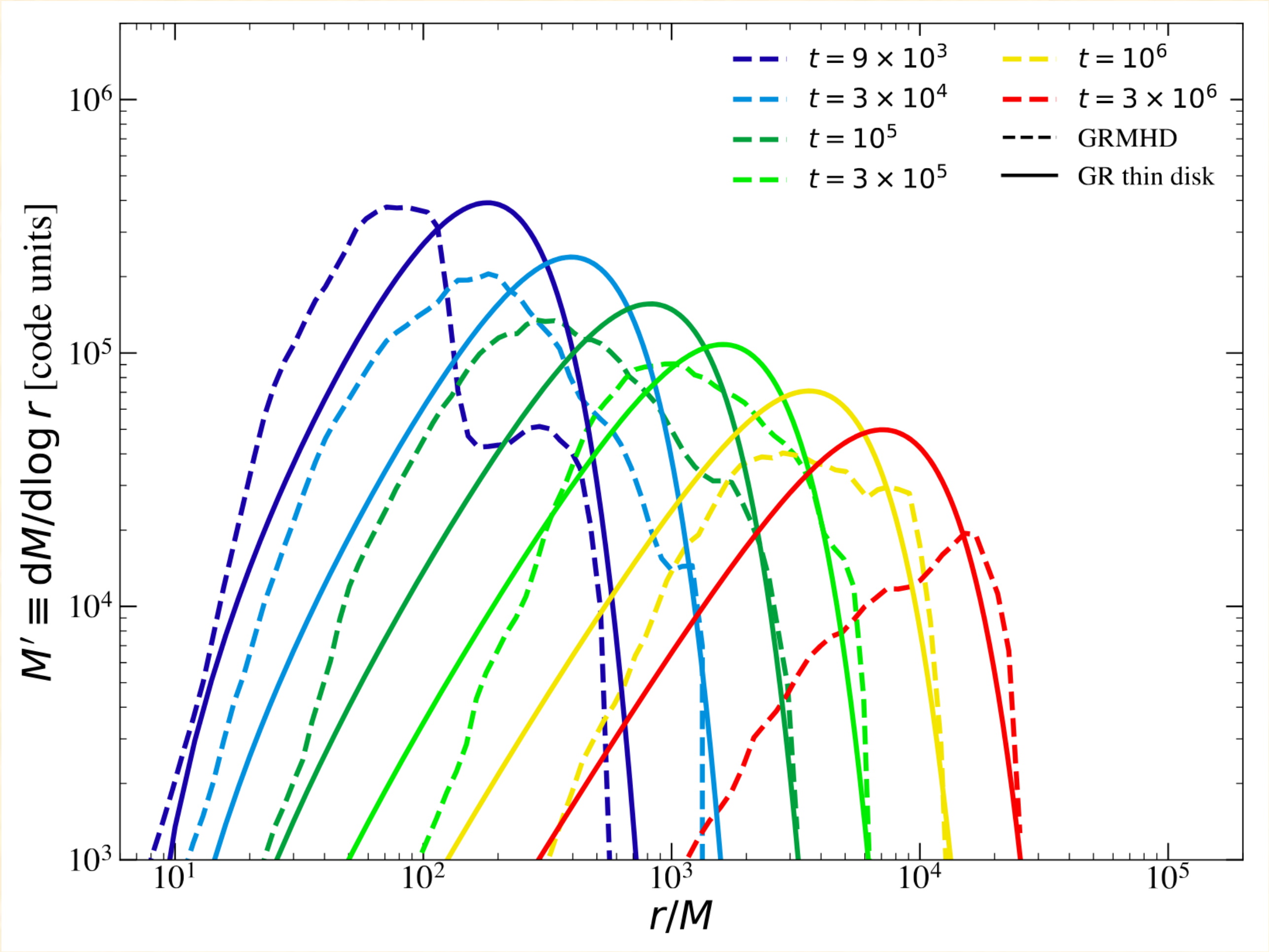
Mass accretion rate

Direct simulation

Cyclic Zoom



Long-term evolution of Mass Profiles

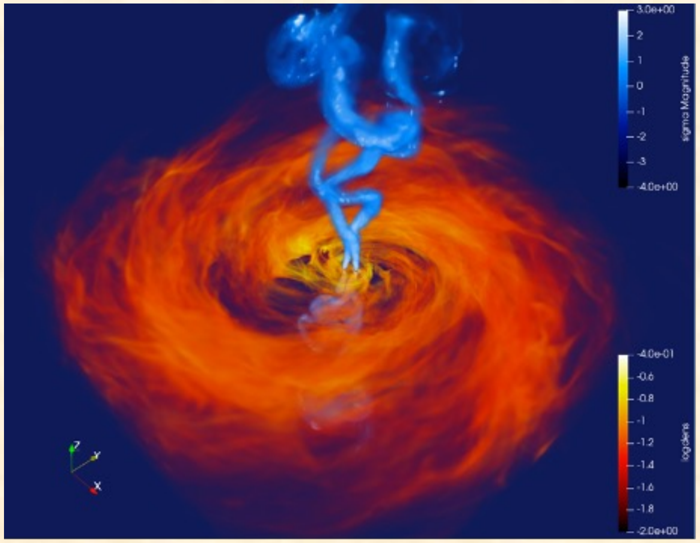


Solid lines = analytic solution with constant stress

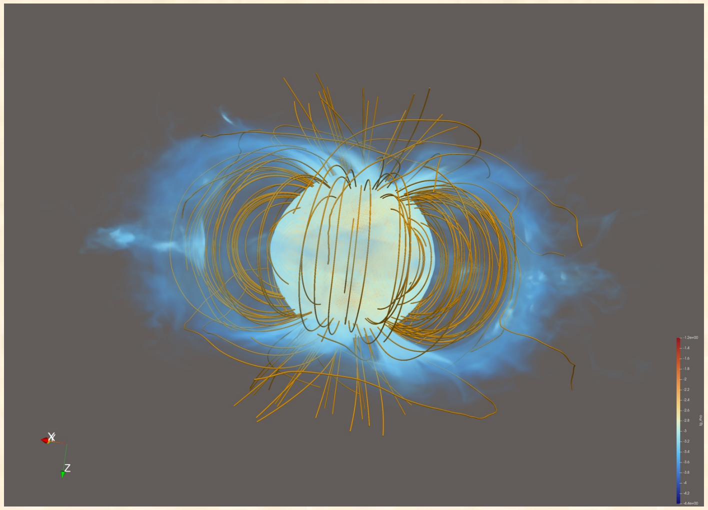
Discrepancy at late times due to mass loss via winds.

Mummery+ 2026

Future applications



Circumbinary disks with GRMHD, radiation transport and dynamical spacetimes
(with H. Zhu, A Dittman)



Magnetosphere-disk interaction in NS and T-Tauri stars
(with C. Fairbairn, Z. Zhu)

Some observationally motivated questions

How does super-Eddington accretion occur?

Highly non-spherical flows, additional cooling from turbulent transport is important.

How do accretion disks form coronae?

With MRI, dissipation not proportional to density.
Dissipation in diffuse upper layers produces hot corona.

Can we compute synthetic spectra and test continuum fitting models?

Preliminary spectra are promising.
We can compute light curves to compare to observations.
Much further work underway.

Summary

- Direct numerical simulation of radiation-dominated accretion flows can now used to study quasars, X-ray binaries, ULXs, feedback and the growth of BHs.
- Super-Eddington disks:
  - Strongly radiation pressure dominated
  - Radiation driven outflows with v ~ 0.1-0.4c
  - Radiative efficiency 5-7%, and decreases when $\dot{M} > 100\dot{M}_{\rm Edd}$
- Sub-Eddington disks:
  - Appear to be thermally stable, perhaps due to magnetic pressure
  - Radiation viscosity important in upper layers
  - Hot, corona-like region with $T \sim 10^7 - 10^8$ K
- Much more work to be done (lightcurves, spectra, full GR-RT, line-driving, etc.)