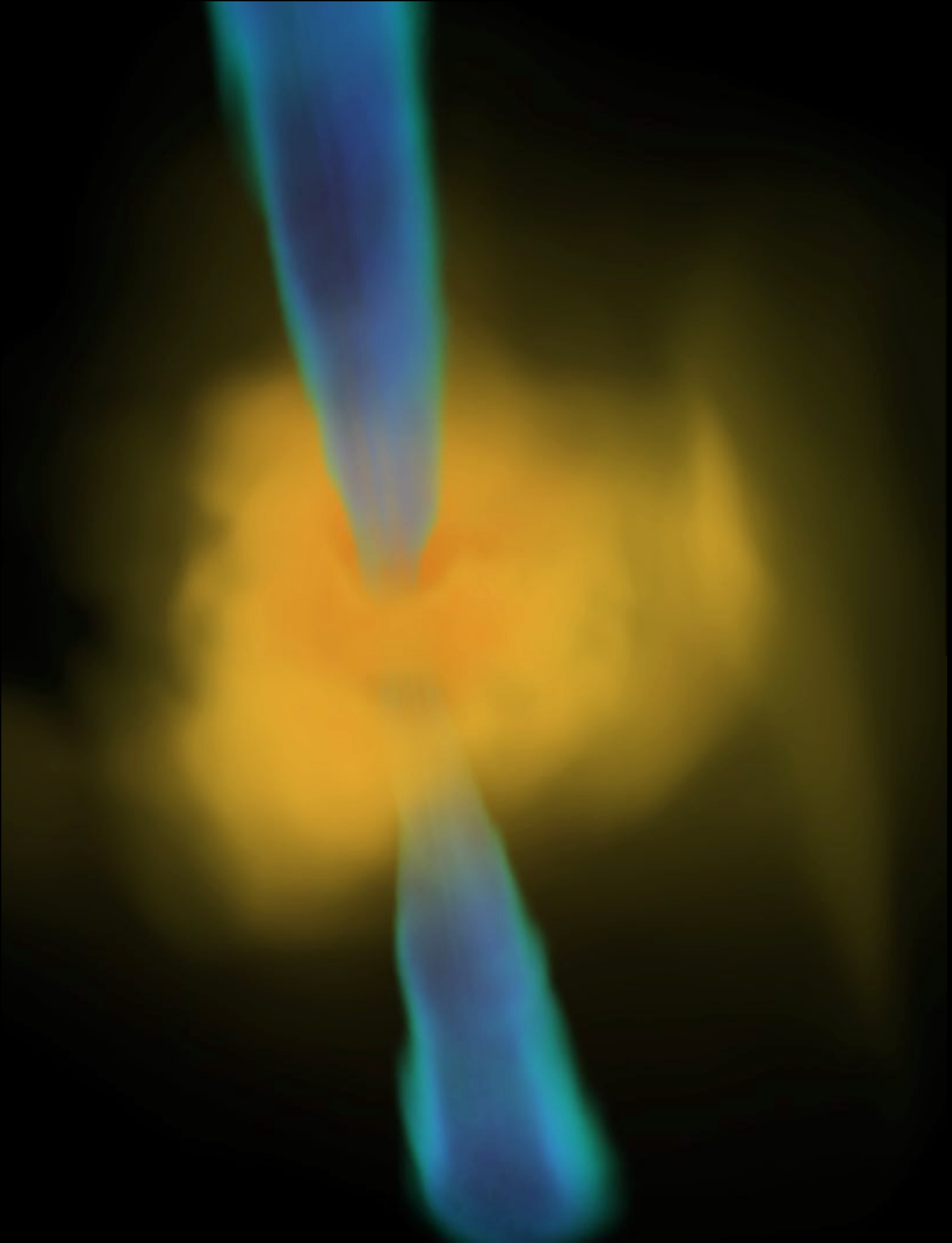

Simulating MAD Super-Eddington Accretion and Outflow Around Stellar-Mass Black Holes

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+Jane Dai, Tassos Fragos, Matthew Middleton, Zepei Xing et al.

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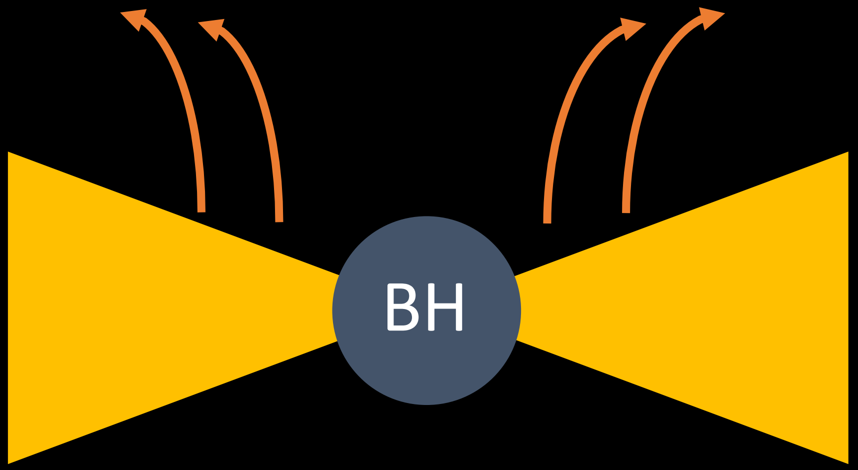
Super Eddington accretion onto stellar-mass black holes



- Geometrically and optically thick disk
- Strong wind and possibly strong jet
- Photon-trapping

Shakura & Sunyaev 1973, Begelman 1978, Abramowicz et al. 1988

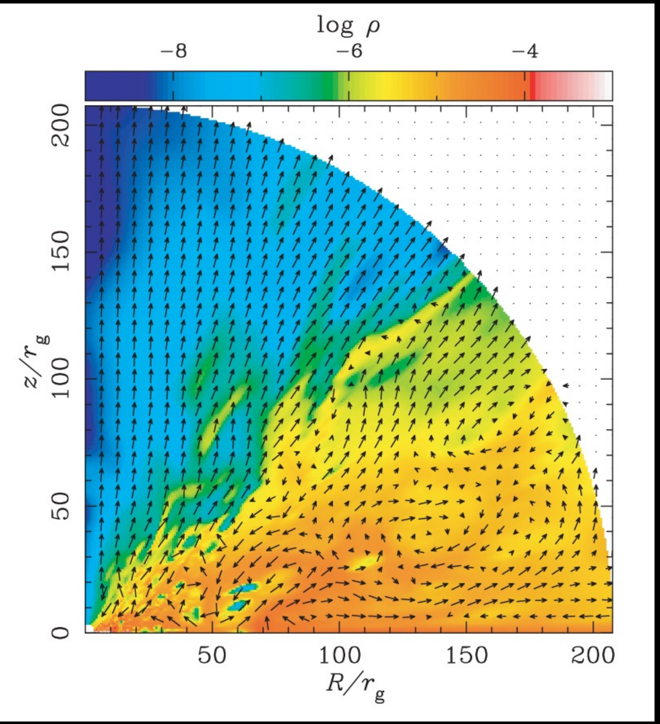
- Extragalactic sources
- Extreme X-ray luminosity ($L_X > 10^{39}$ erg s^{-1})
- Super-Eddington accreting BHs or neutron stars

Review by Kaaret, Feng & Roberts 2017

Ultra-luminous X-ray Sources (ULXs)

ULX8 in M51b
Credit: NASA/CXC/Caltech/M. Brightman et al.

Super-Eddington accretion flow simulations



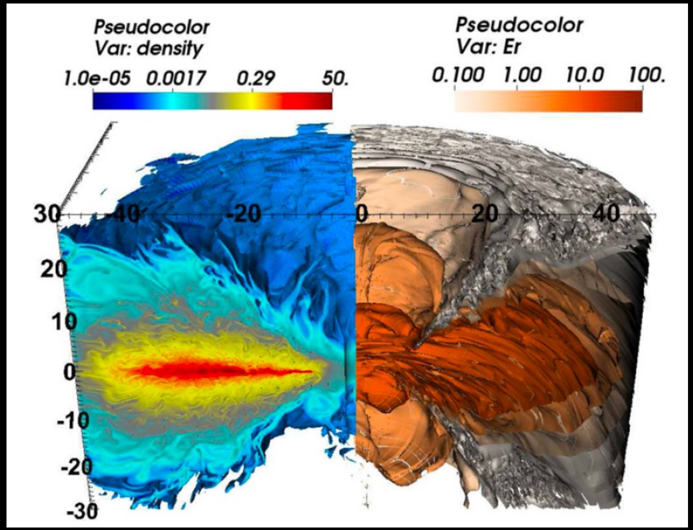
- Novel (GR) Radiation MHD simulations

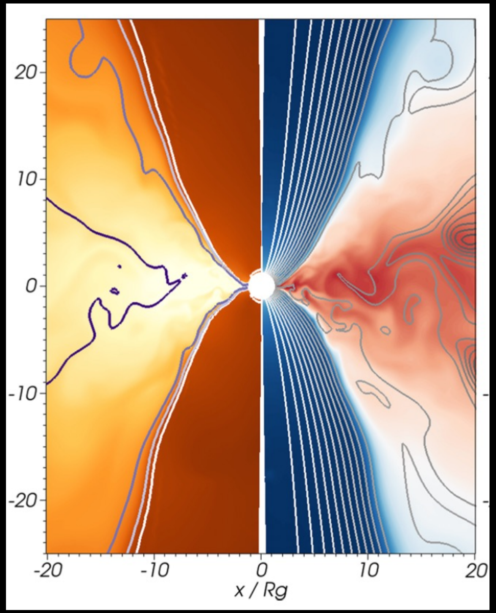
However:

- Different setup of disk and initial conditions
- A small number of parameter sets
- Small equilibrium region/ simulation box

Need:

- A large number of systematic 3D large-scale simulations to understand the effects of BH mass, spin and accretion rate





Ohsuga et al. 2005
Takahashi, Ohsuga et al. 2016
Utsumi et al. 2022
Jiang et al. 2014
Sadowski et al. 2014, 2016
McKinney et al. 2014, 2015

3D Radiation GRMHD simulations code HARMRAD

(Gammie et al. 2003; McKinney et al. 2014, 2015)

Rest Mass

$$\nabla_\mu(\rho u^\mu) = 0$$

Energy-Momentum

$$T^\mu_\nu = T^{MA\mu}_{\ \ \ \nu} + T^{EM\mu}_{\ \ \ \nu} = \mathrm{G}_\nu$$

Radiation

$$\mathrm{R}^\mu_\nu = -\mathrm{G}_\nu$$

$$\nabla_\mu\left(T^\mu_\nu + \mathrm{R}^\mu_\nu\right) = 0$$

Magnetic Flux

$$\partial_t\left(\sqrt{-g}B^i\right) = -\partial_j\left[\sqrt{-g}\left(b^j u^i - b^i u^j\right)\right]$$

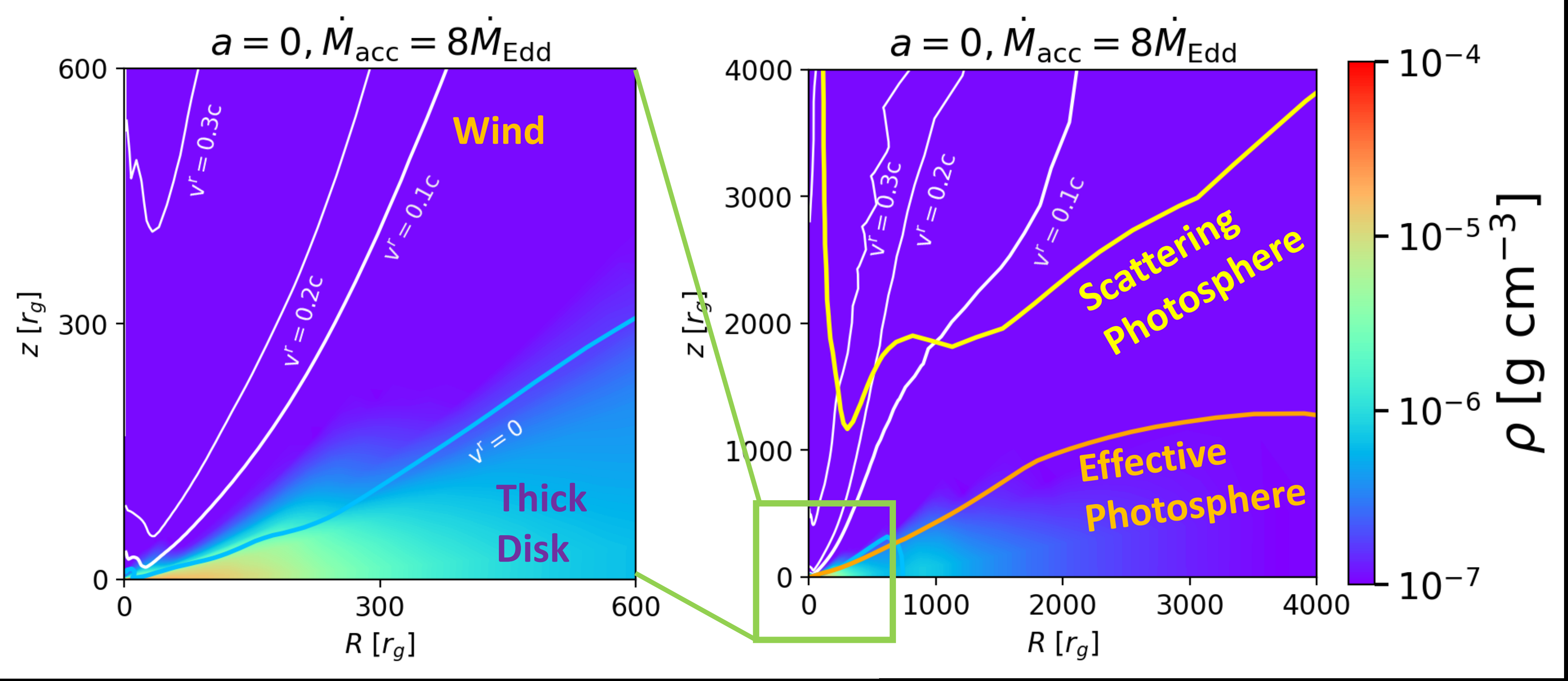
- Co-evolve radiation and plasma
- M1 approximation for radiation
- Radiative transfer physics:
  - Electron scattering
  - Absorption and emission (grey opacity)
  - Thermal Comptonization

A suite of super-Eddington *MAD* simulations to study ULXs

- 30 x 3D Radiation GRMHD simulations of aligned super-Eddington disks
- Black hole mass: 5 $M_\odot$, 15 $M_\odot$, 30 $M_\odot$
- Black hole spin: 0.0, 0.9
- Accretion rates $\sim$ a few – few $\times 100\ \dot{M}_{\rm Edd}$
- Final state: Magnetically Arrested Disks (MADs)
- Large simulation boxes ($\sim 8000\ r_g$)
- Long simulation time ($> 30{,}000\ t_g$)

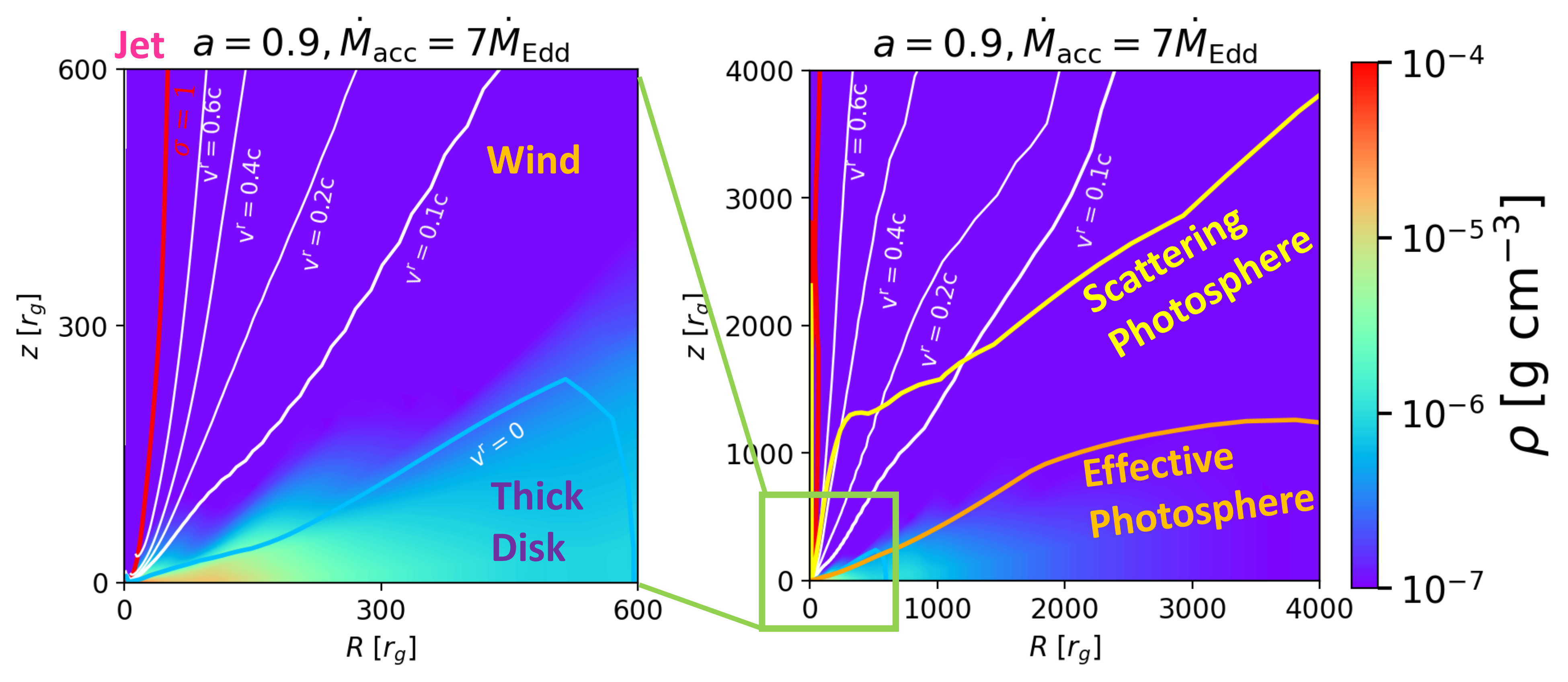
Ultra-fast outflows

- $a = 0$ models can power ultrafast outflows ($v^r < 0.5c$)



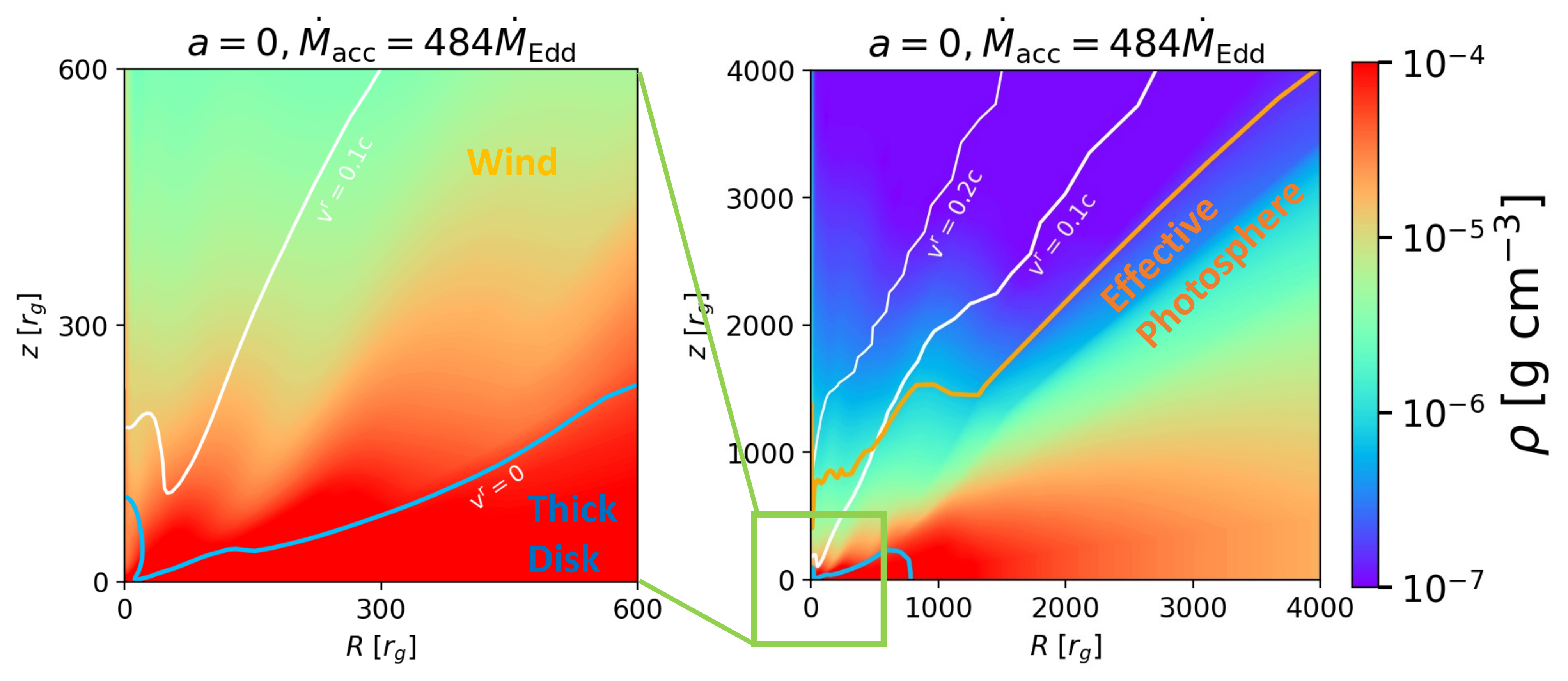
Ultra-fast outflows and relativistic jets

- $a = 0.9$ models can power faster UFOs ($v^r > 0.5c$) and BZ jets

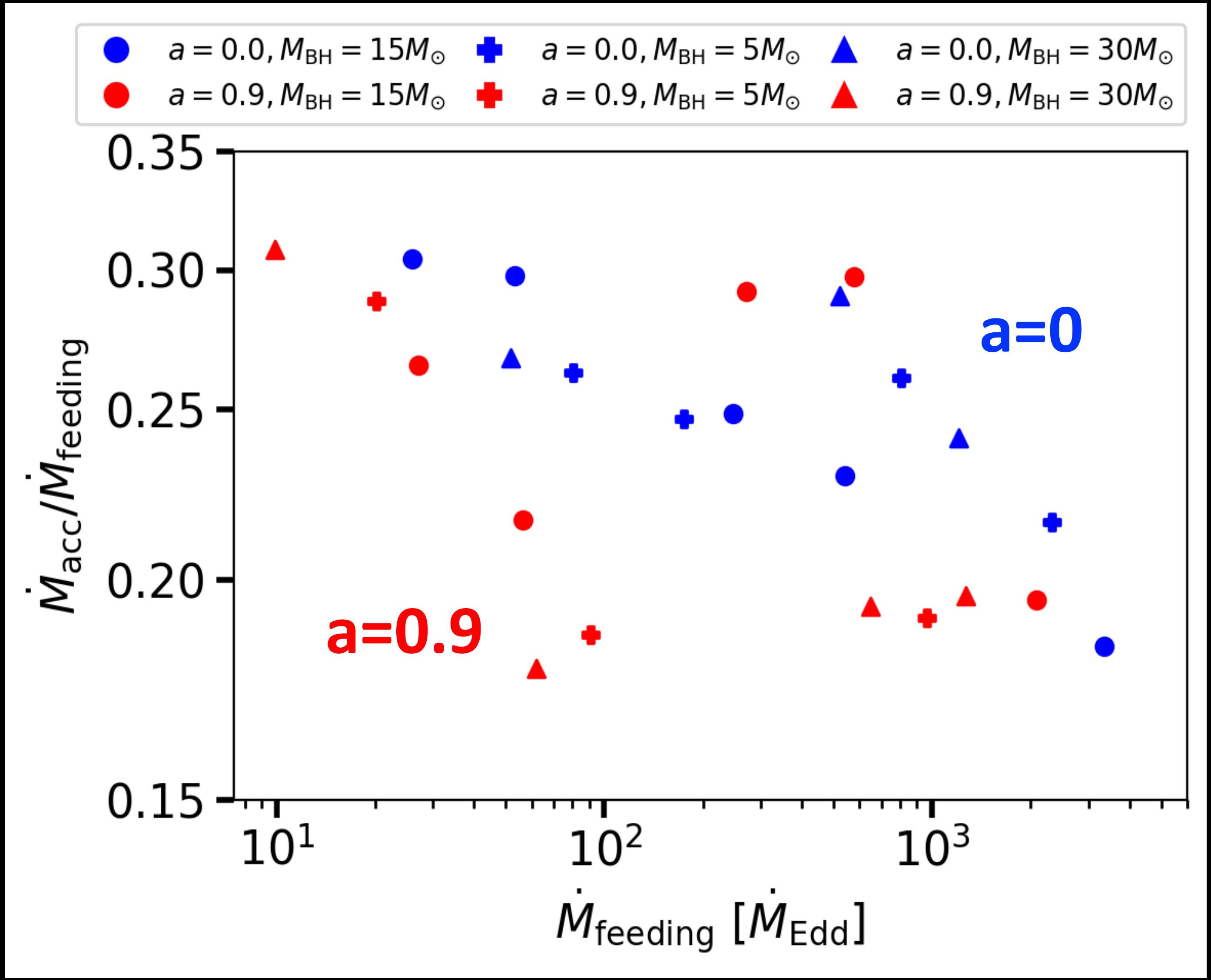


Hyper-Eddington accretion

- $a = 0$ models but higher accretion rates → lower wind speeds



Accretion vs. Outflow mass rate

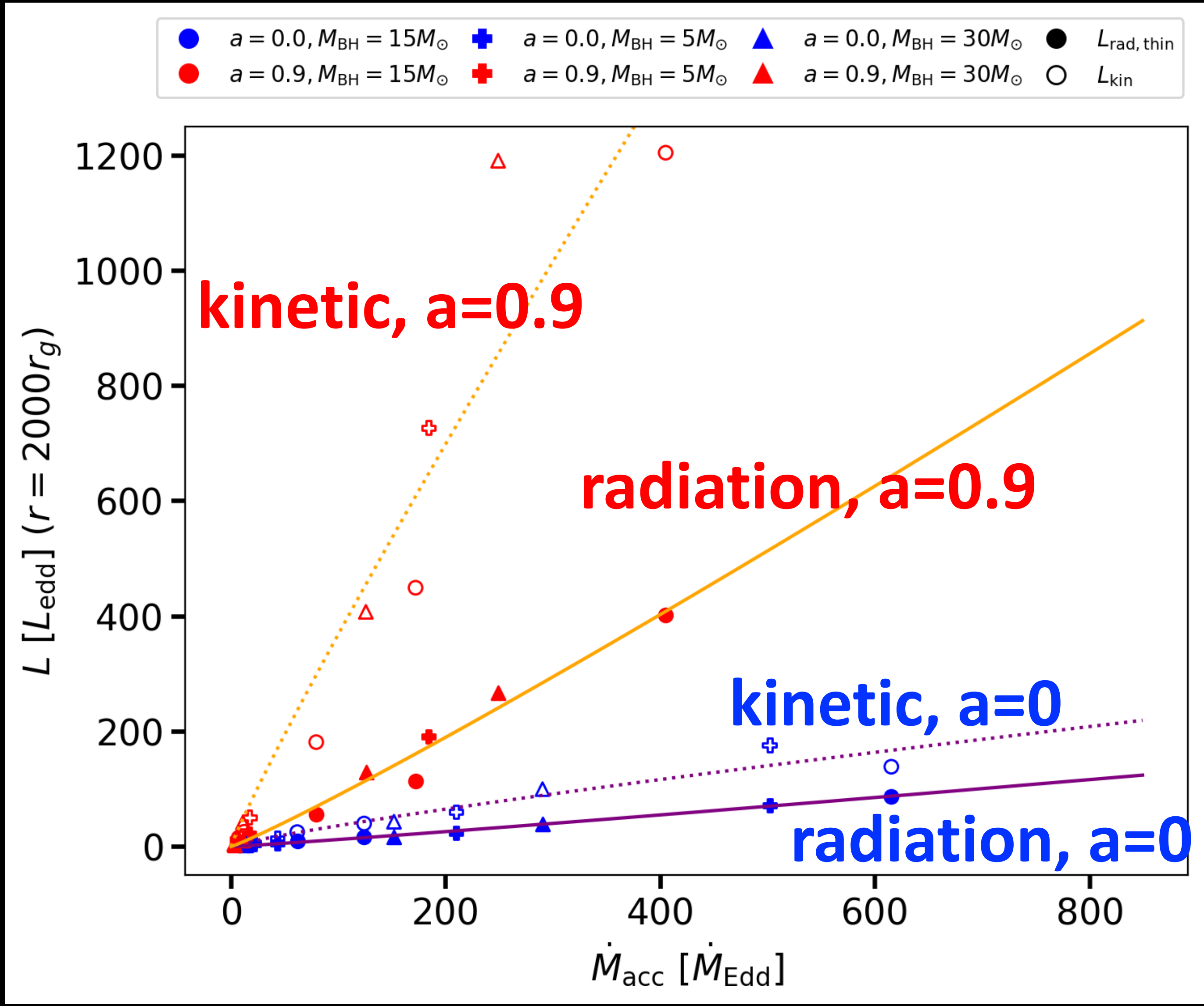


Feeding rate

$$\dot{M}_{feeding} = \dot{M}_{acc} + \dot{M}_{wind}$$
$$(\dot{M}_{wind} \text{ at } r = 2000\ r_g)$$

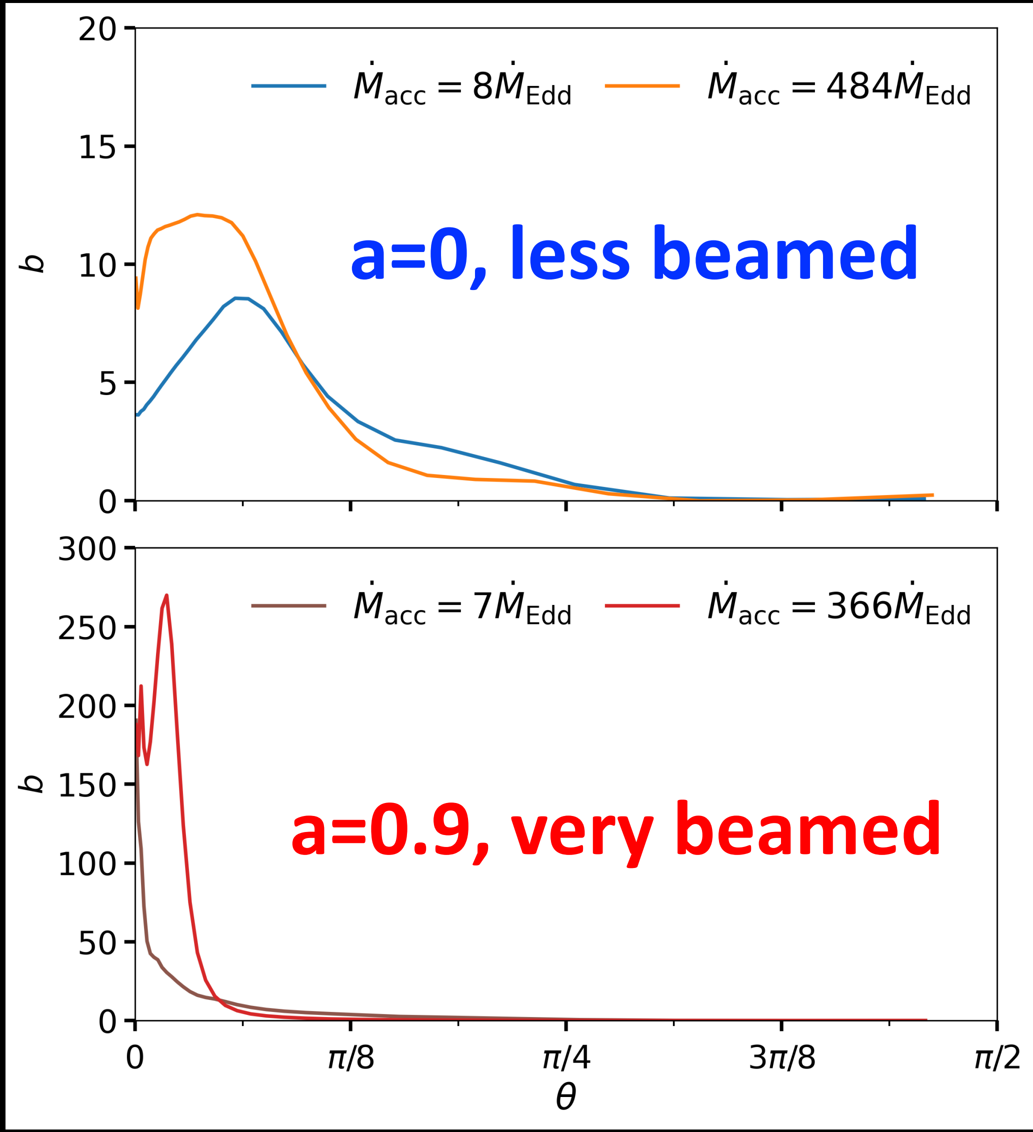
- $> 70\%$ of the gas flows out as the wind
- Sensitive to accretion rate (more wind for larger $\dot{M}_{acc}$)
- Insensitive to BH mass

Kinetic and radiative luminosity (Wind Only)



- Kinetic luminosity L_{kin} > radiative luminosity $L_{\mathrm{rad,thin}}$ (optically-thin wind only)
- Energy output sensitively depends on BH spin and scales with $\dot{M}_{\mathrm{acc}}$
- Insensitive to BH mass

Beaming of the radiation



- Beaming factor b = ratio of the isotropic radiative luminosity to the total radiative luminosity

$$b(r,\theta) = \frac{L_{\mathrm{rad,iso}}(r,\theta)}{L_{\mathrm{rad}}(r)}$$

- The radiation is beamed near the polar direction

- The radiation in the outflows in $a = 0.9$ models are very beamed

Key take-away messages

- We conduct 30 simulations of MAD state super-Eddington accretion flows around stellar-mass BHs.
- Super-Eddington winds carry a lot of mass, and kinetic/radiative energy, which depends on both BH spin and accretion rate.
- The emitted radiation is much more beamed when the BH spins fast.
- The outputs are insensitive to BH mass (within 5-30 $M_{\odot}$).

Kwan, Dai, Fragos, et al. in prep.