Global 3D radiation MHD simulations of AGN accretion disks

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X-ray Binaries Do Not scale to AGNs

$$T_{eff} \approx 5 \text{ keV} \left(\frac{M_{\rm BH}}{M_\odot}\right)^{-1/4} \left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right)^{1/4} \left(\frac{r}{r_g}\right)^{-3/4}$$

X-ray binaries

$$T \sim 2 \times 10^7 K \quad \rho \sim 0.01 g/cm^3 \quad P_r/P_g \sim 15$$

AGNs

$$T \sim 2 \times 10^5 K \quad \rho \sim 10^{-10} g/cm^3 \quad P_r/P_g \sim 10^3$$

Effects of Very Strong radiation pressure:

- Compressibility
- radiation viscosity
- Thermal Instability

See Omer's Talk:
Omer convinces us
that accretion disks in AGNs
are interesting.

The Input Physics

Jiang et al. (2014)

Ideal MHD

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{P}^*) = -\boldsymbol{S_r}(\boldsymbol{P}) - \rho \boldsymbol{\nabla} \phi,$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -cS_r(E) - \rho \boldsymbol{v} \cdot \boldsymbol{\nabla} \phi,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) = 0. \qquad (1)$$

photon momentum

radiation energy

Radiative Transfer

$$\frac{\partial I}{\partial t} + c\boldsymbol{n} \cdot \nabla I = S.$$

$$S = c\rho\kappa_a \left(\frac{a_r T^4}{4\pi} - I_0 \right) + c\rho\kappa_s \left(J_0 - I_0 \right),$$

Lorentz transformation between lab frame and co-moving frame to handle the velocity dependent source terms.

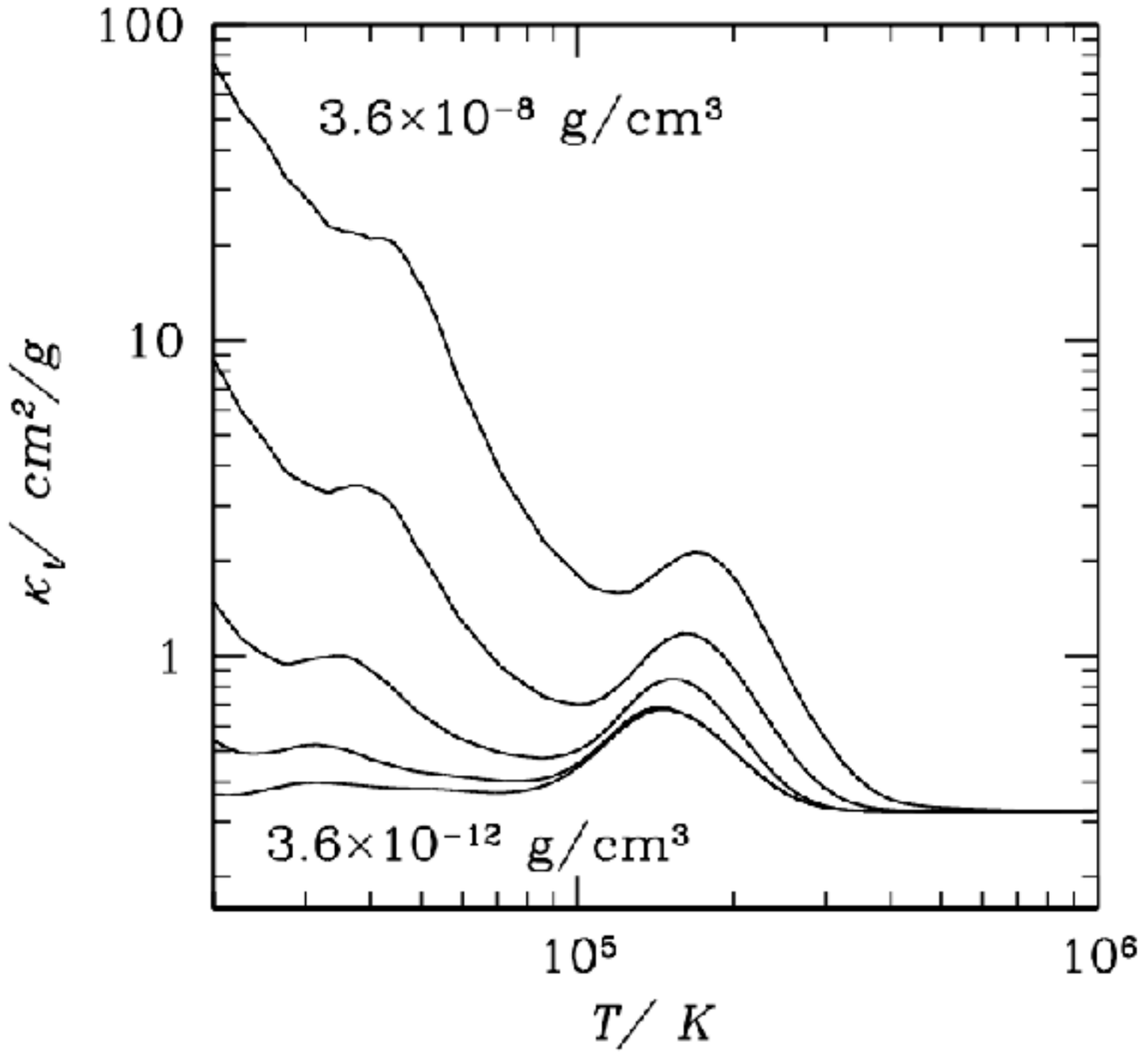
The Input Physics

Jiang et al. (2012)

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{\partial F_r/c^2}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B} + P_g + P_B + \mathbf{P_r}) = 0$$

The Opacity

Paxton et al. (2013,2015)
Jiang et al. (2015)

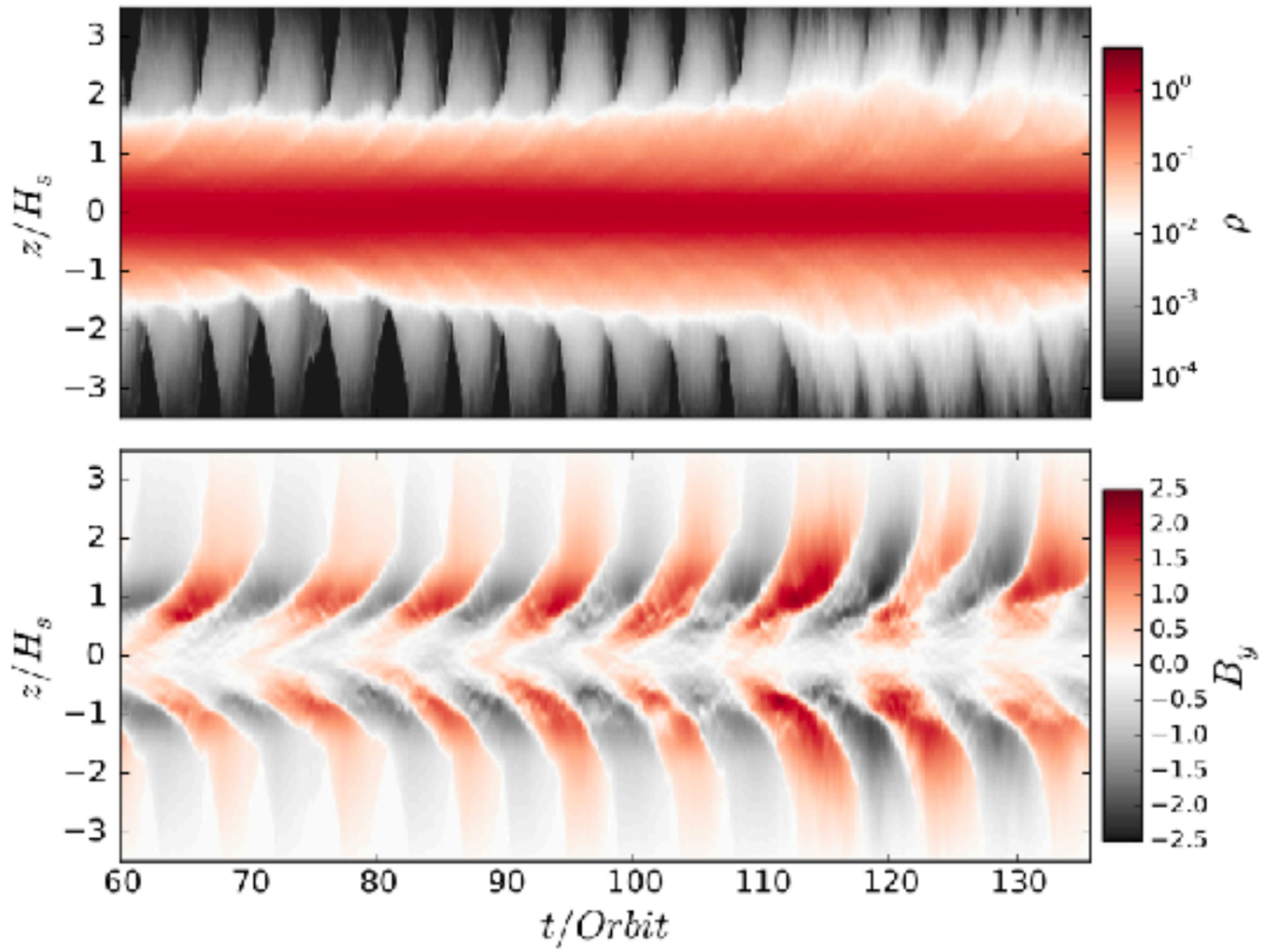


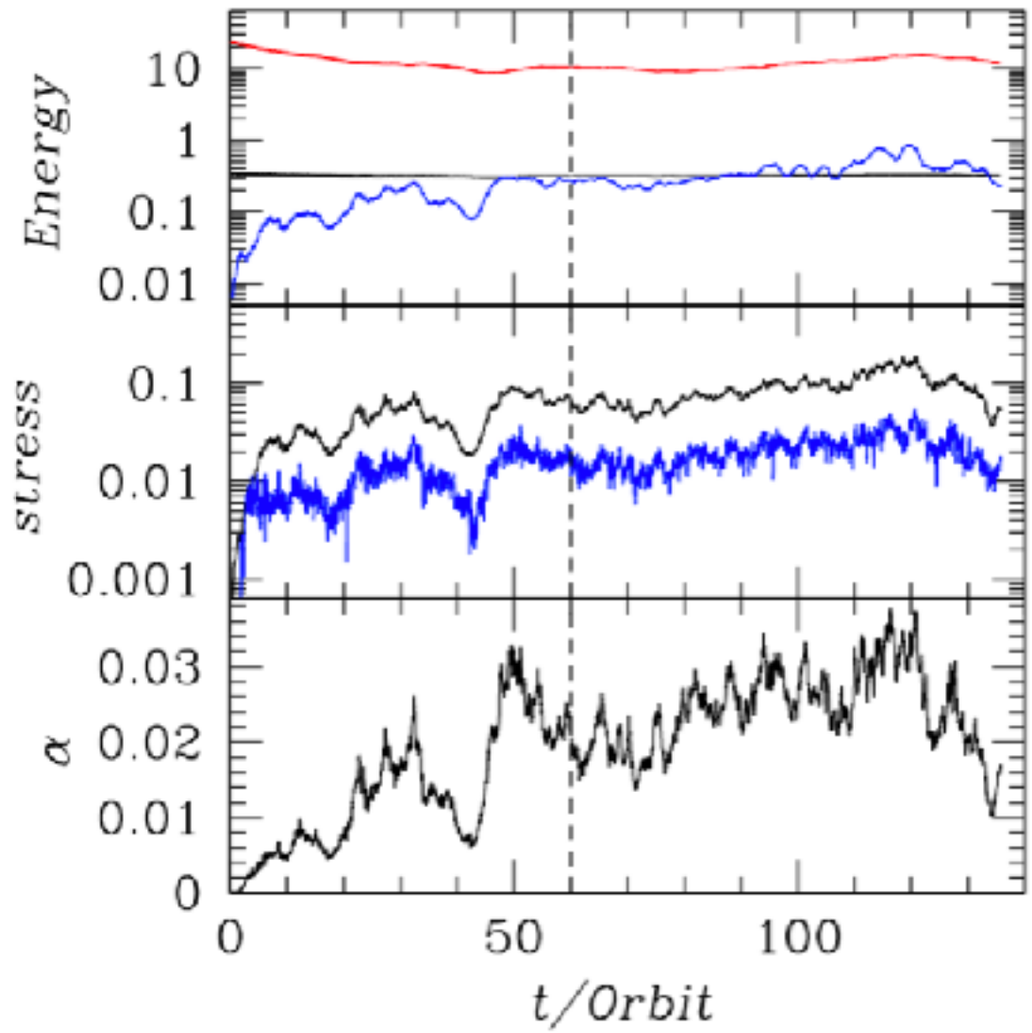
The density and temperature ranges are very similar as in massive star envelopes!

Iron Opacity Peak Changes the Thermal Stability

Jiang et al. (2016)

Iron Opacity

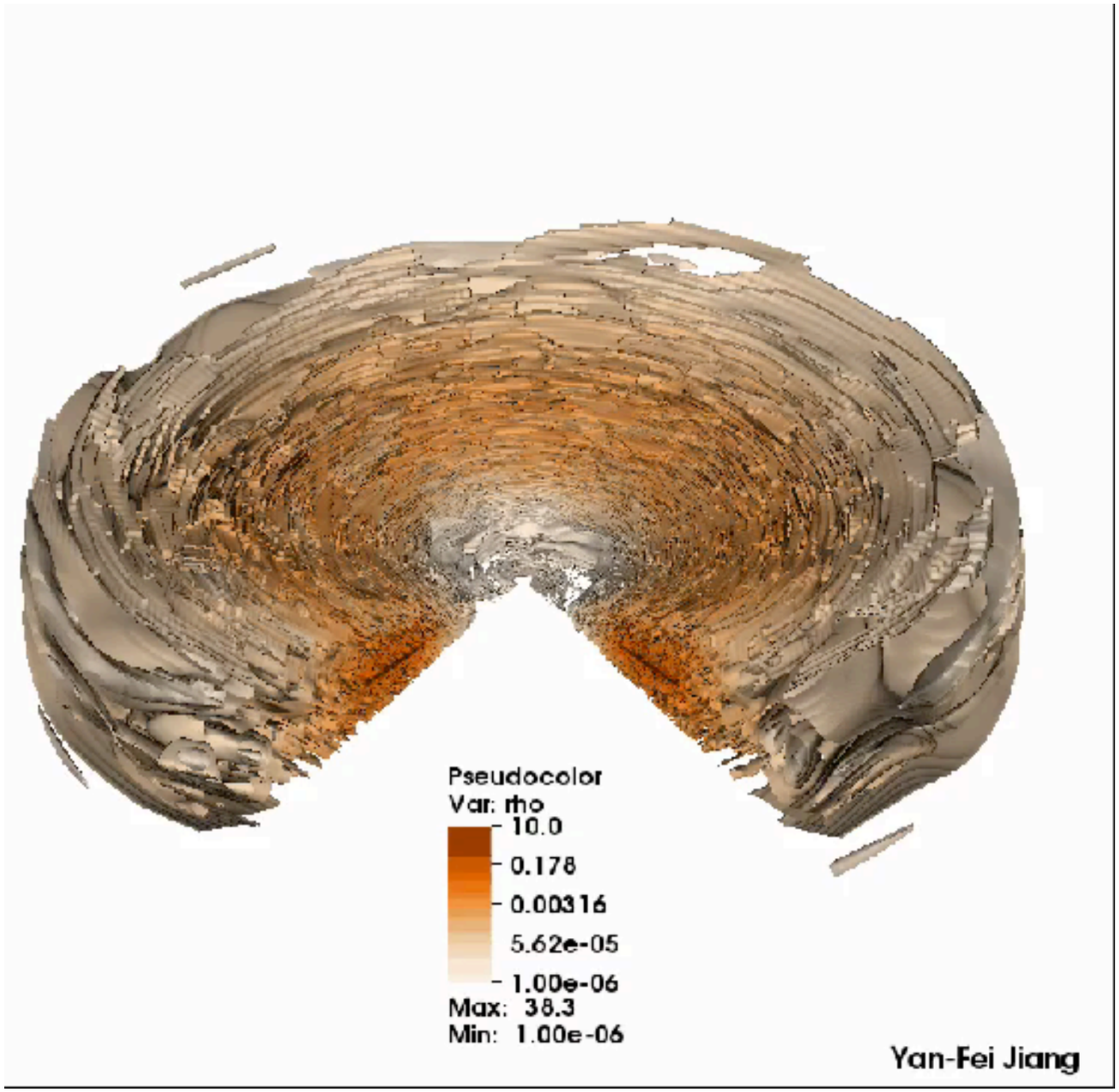


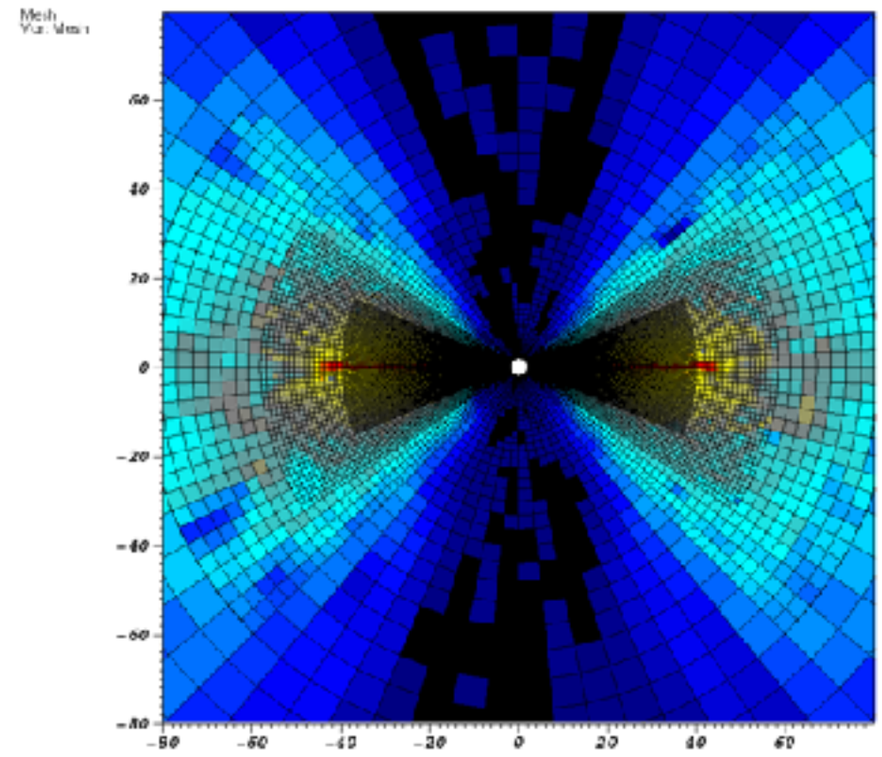


Implications: Dependence of accretion disk properties with metallicity.

Global Radiation MHD Simulations of AGN Accretion Disks

Jiang et al. (2017, in preparation)





Level 0

$$N_r \times N_\theta \times N_\phi = 64 \times 32 \times 64$$

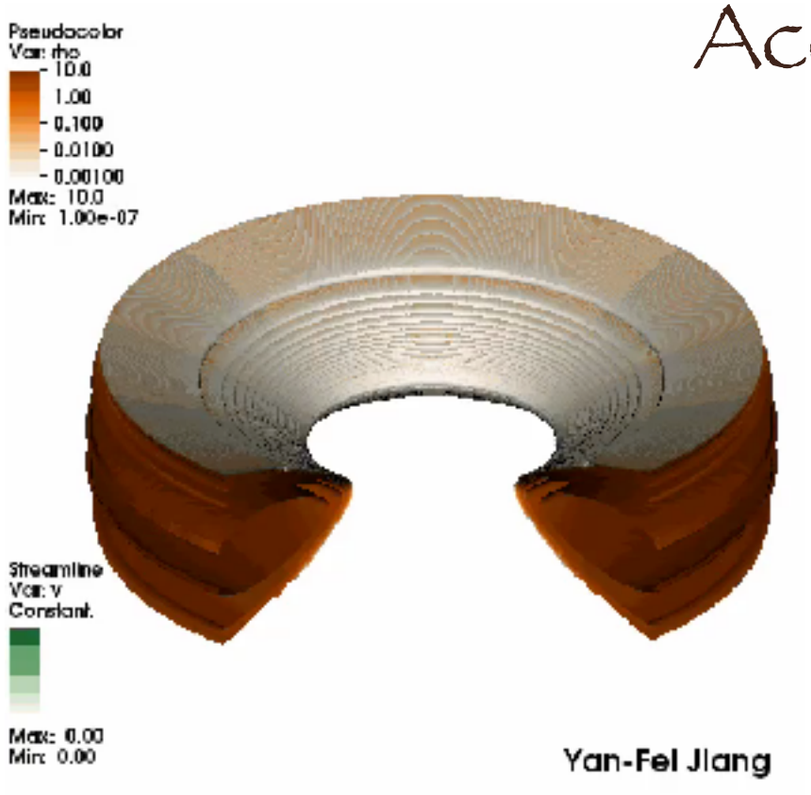
Level 4

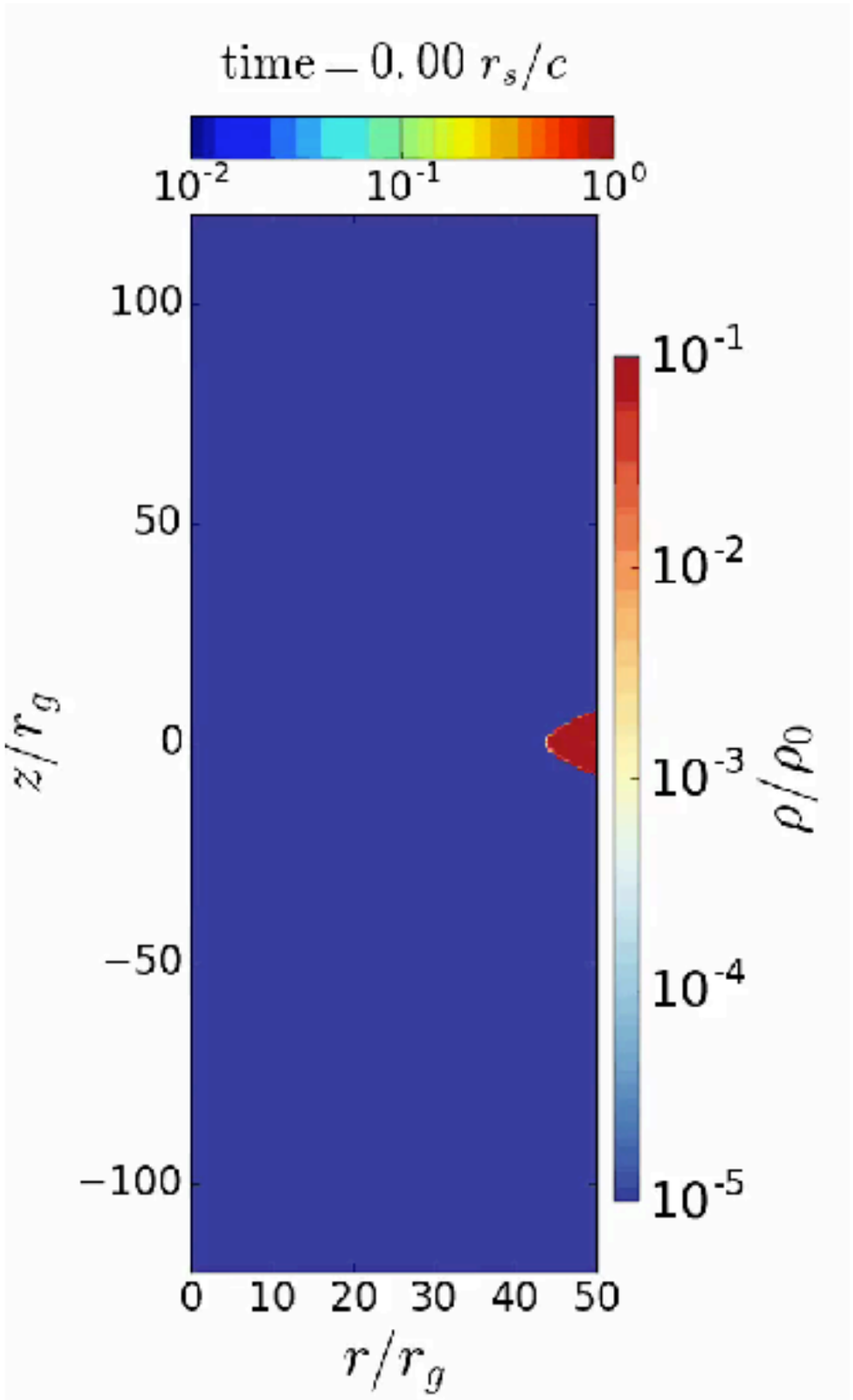
$$N_r \times N_\theta \times N_\phi = 1024 \times 512 \times 1024$$

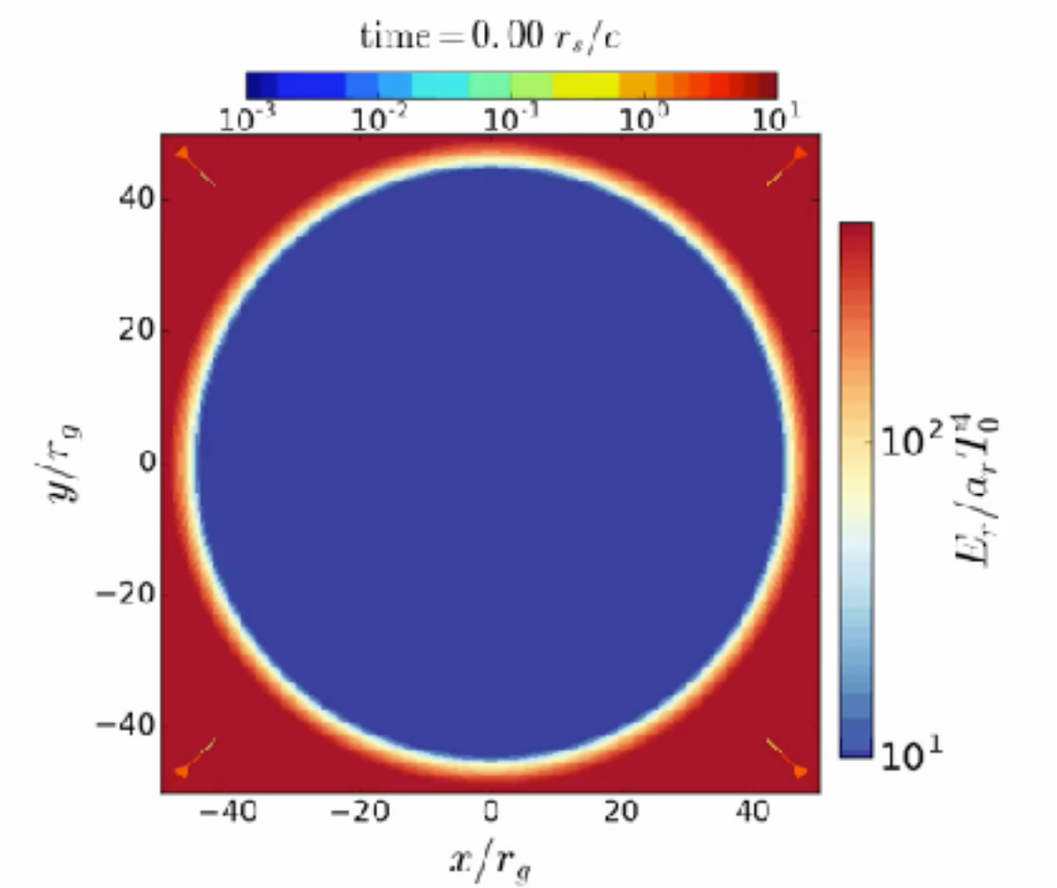
Simulation Parameters

Variables/Units	AGNM1	AGNM2	AGNBM1	AGNBM2
r_i/r_g	80	80	80	50
ρ_i/ρ_0	50	10	10	10
T_i/T_0	12.4	8.4	8.3	8.4
$\Delta r/r$	0.024	0.012	0.012	0.012
$\Delta\theta$	0.024	0.012	0.012	0.012
$\Delta\phi$	0.024	0.012	0.012	0.012
N_n	80	80	80	80
B Loops	Multiple	Multiple	Single	Single

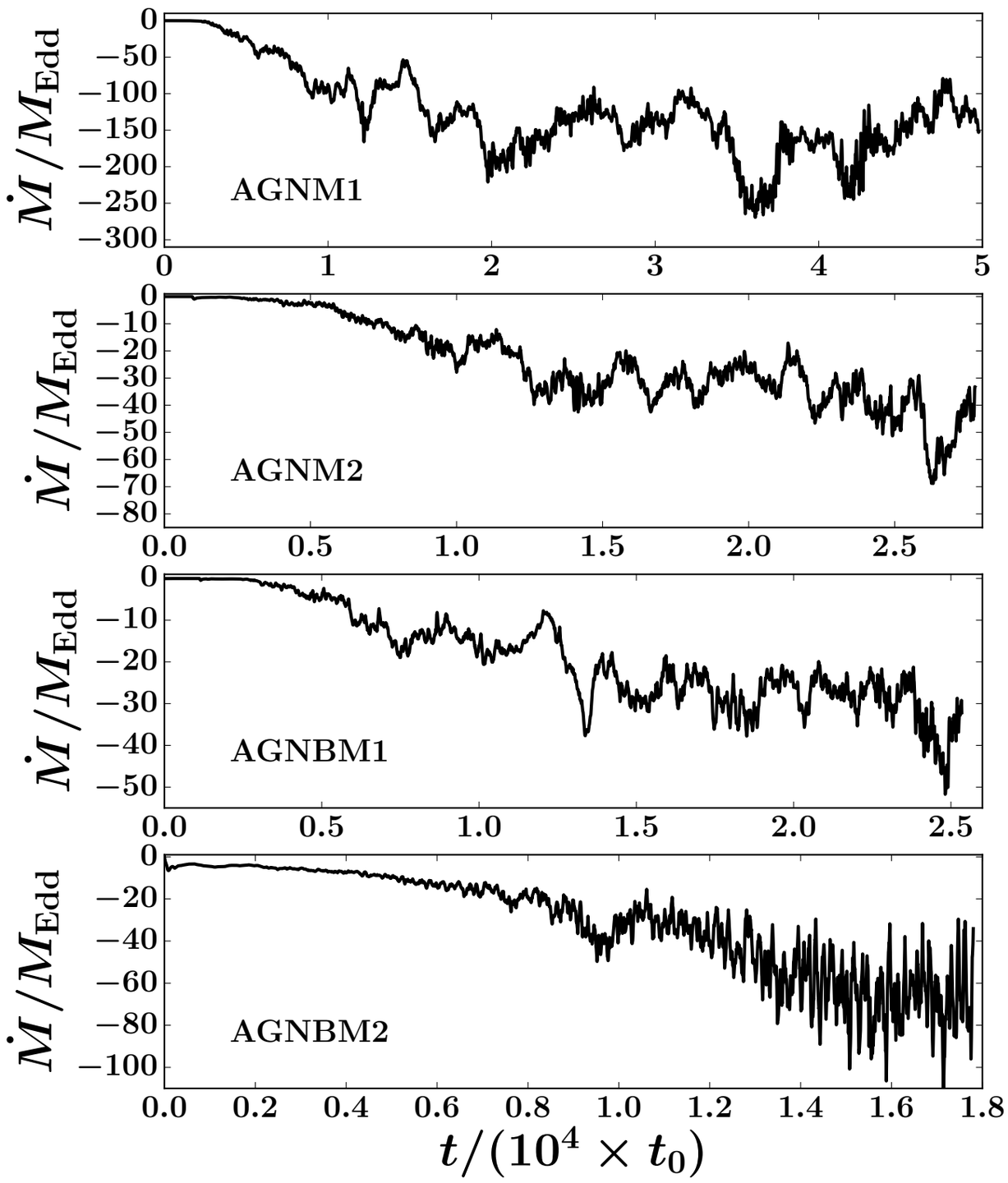
Global Radiation MHD Simulations of AGN Accretion Disks

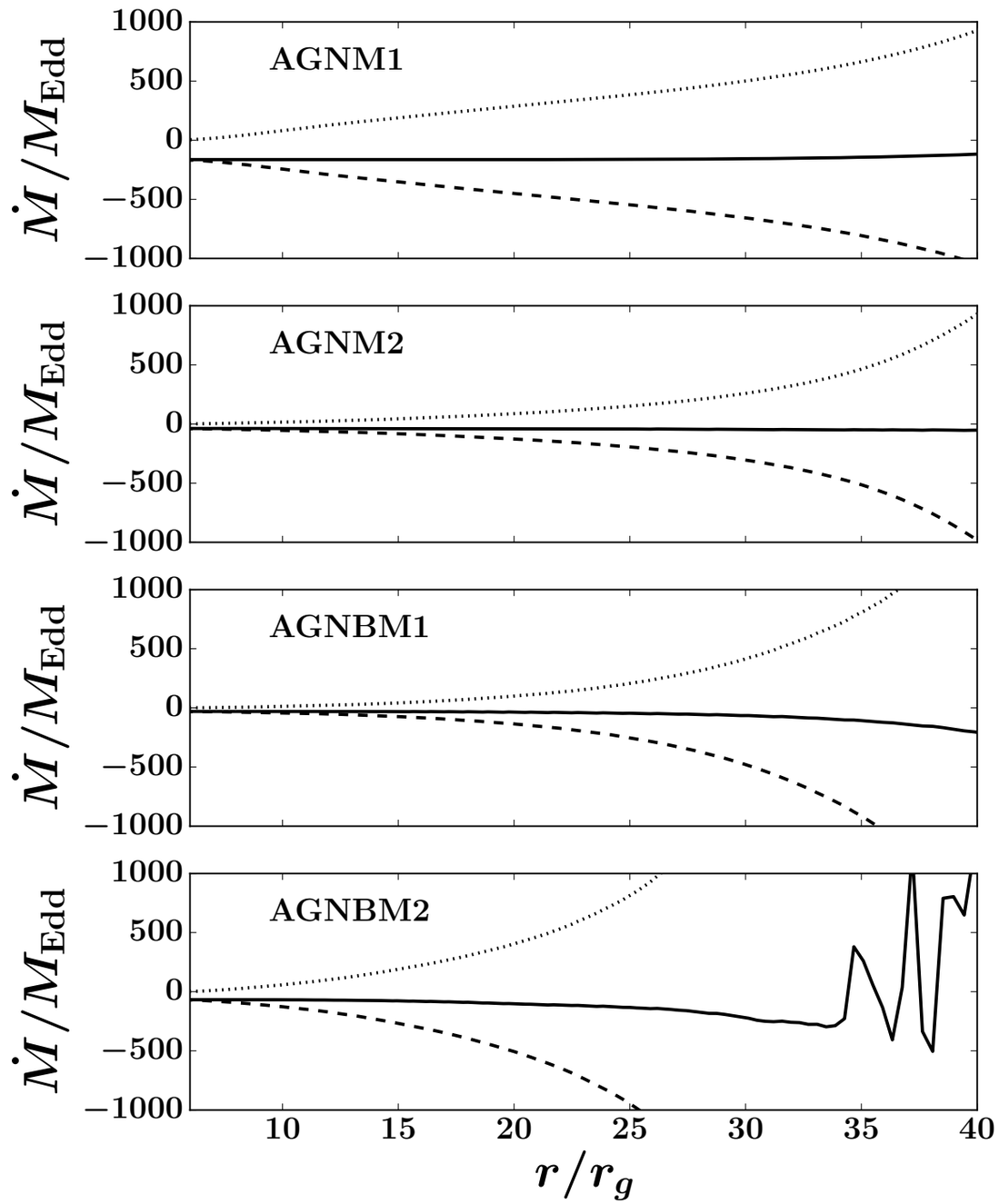




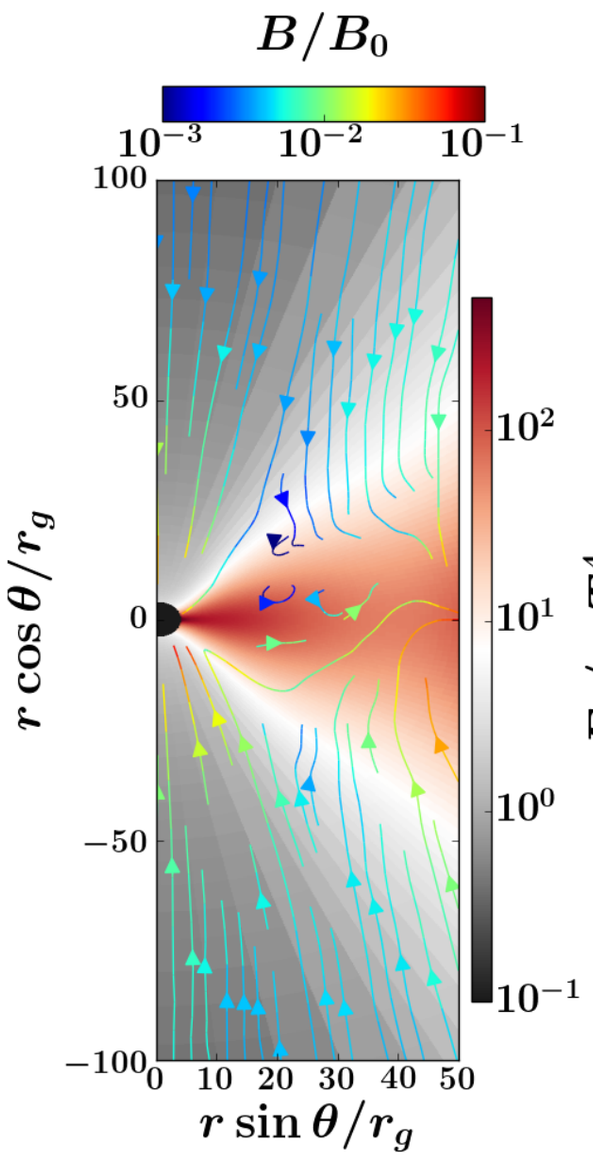


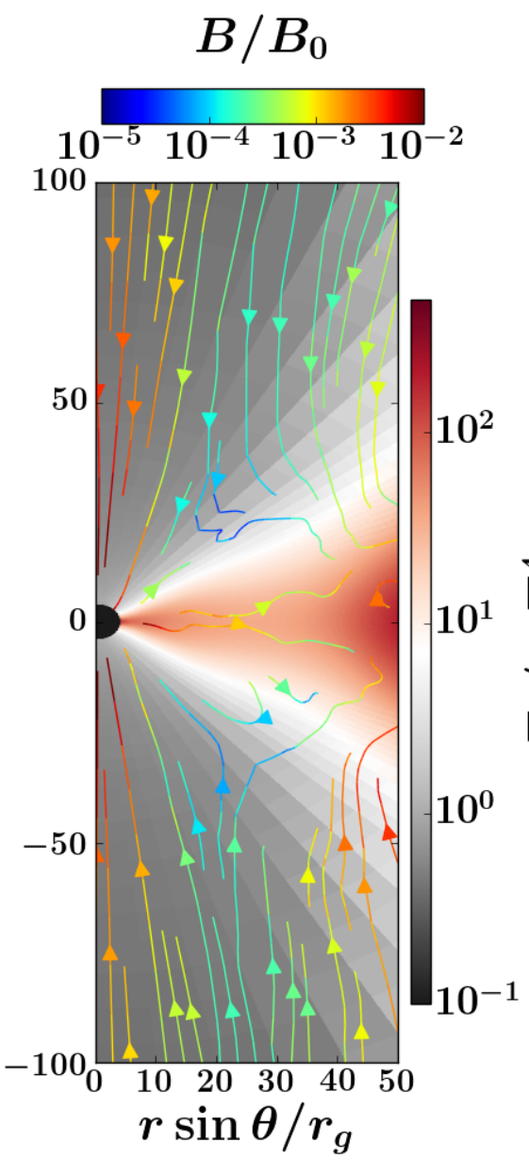
Mass Accretion Rates

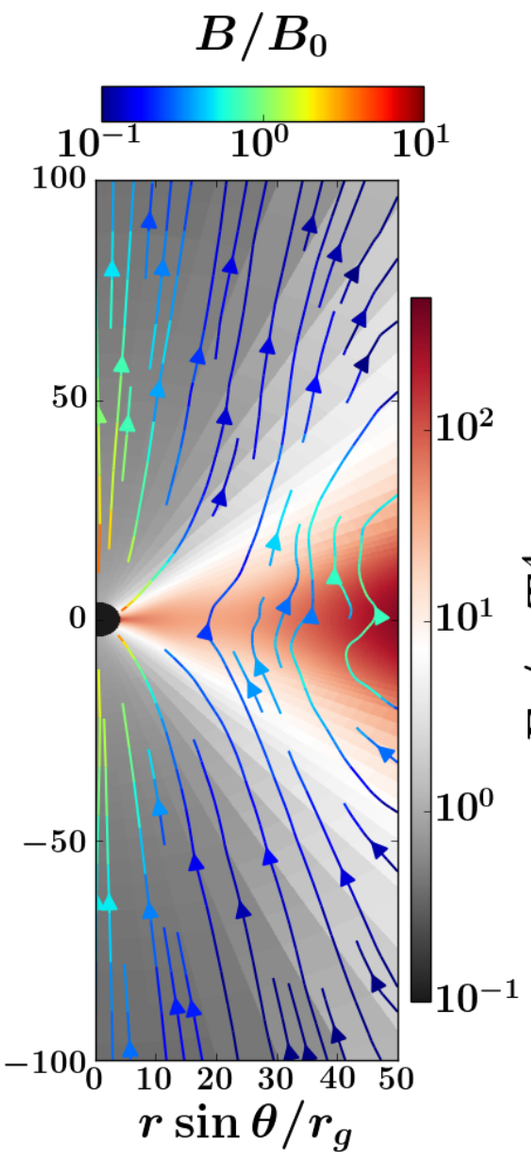


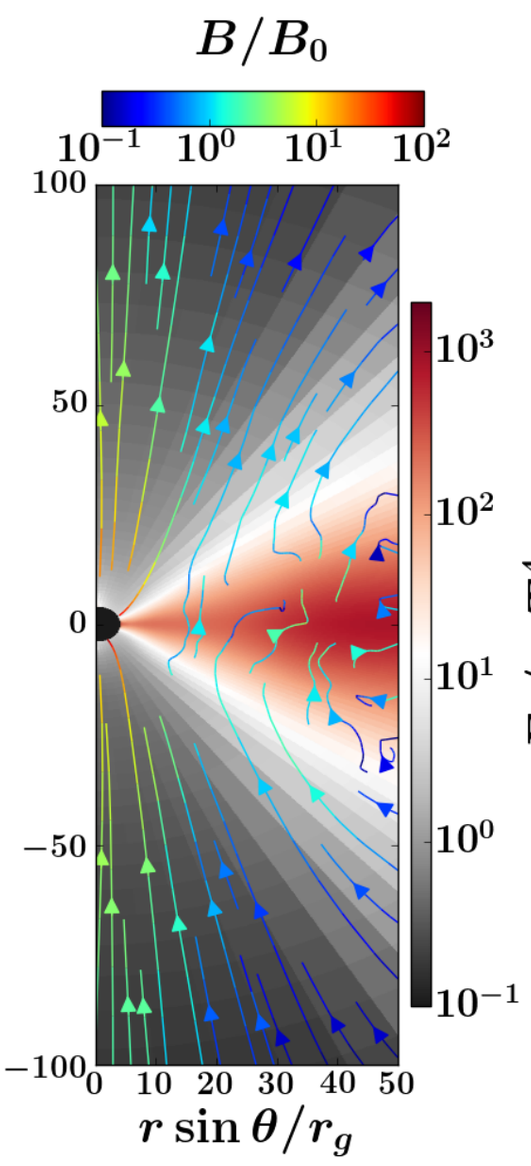


Flow Structures









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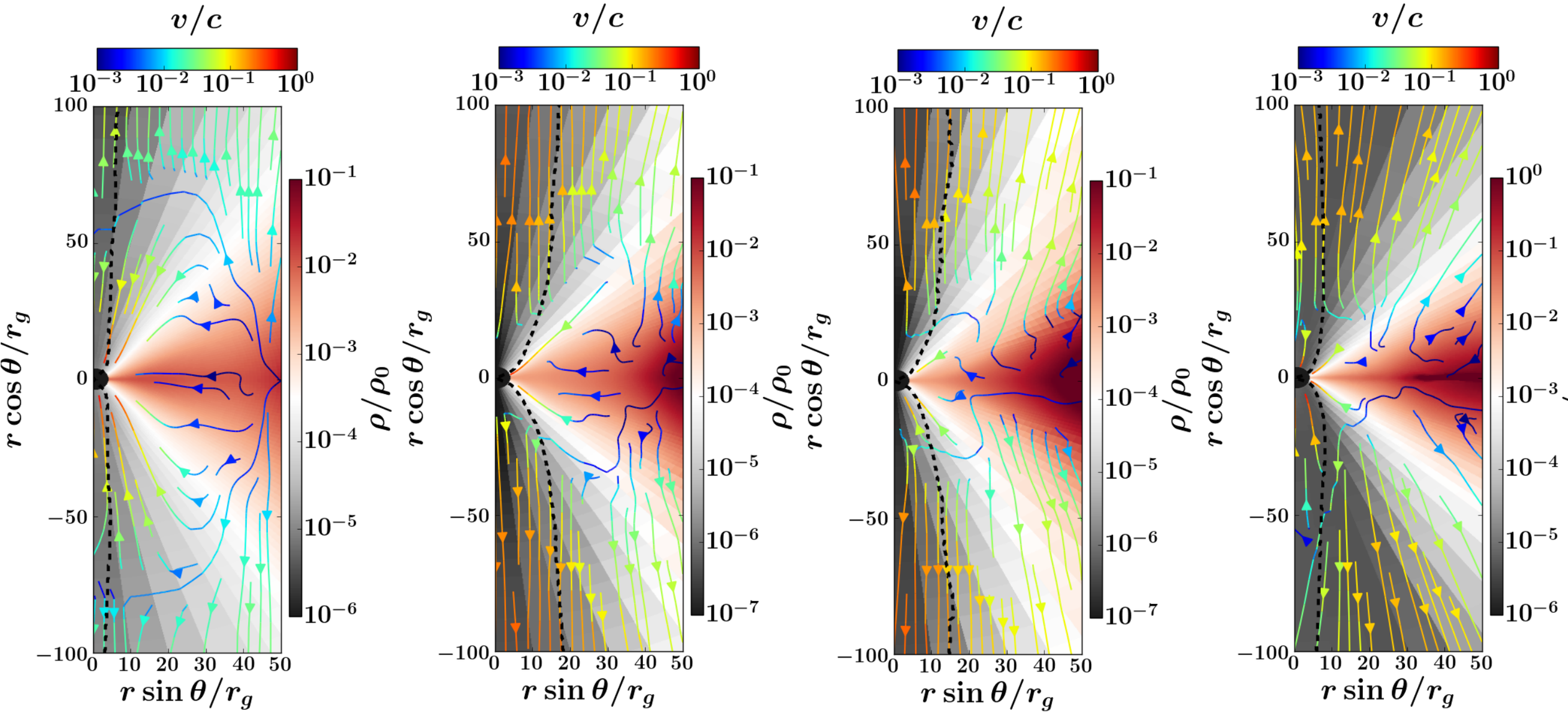
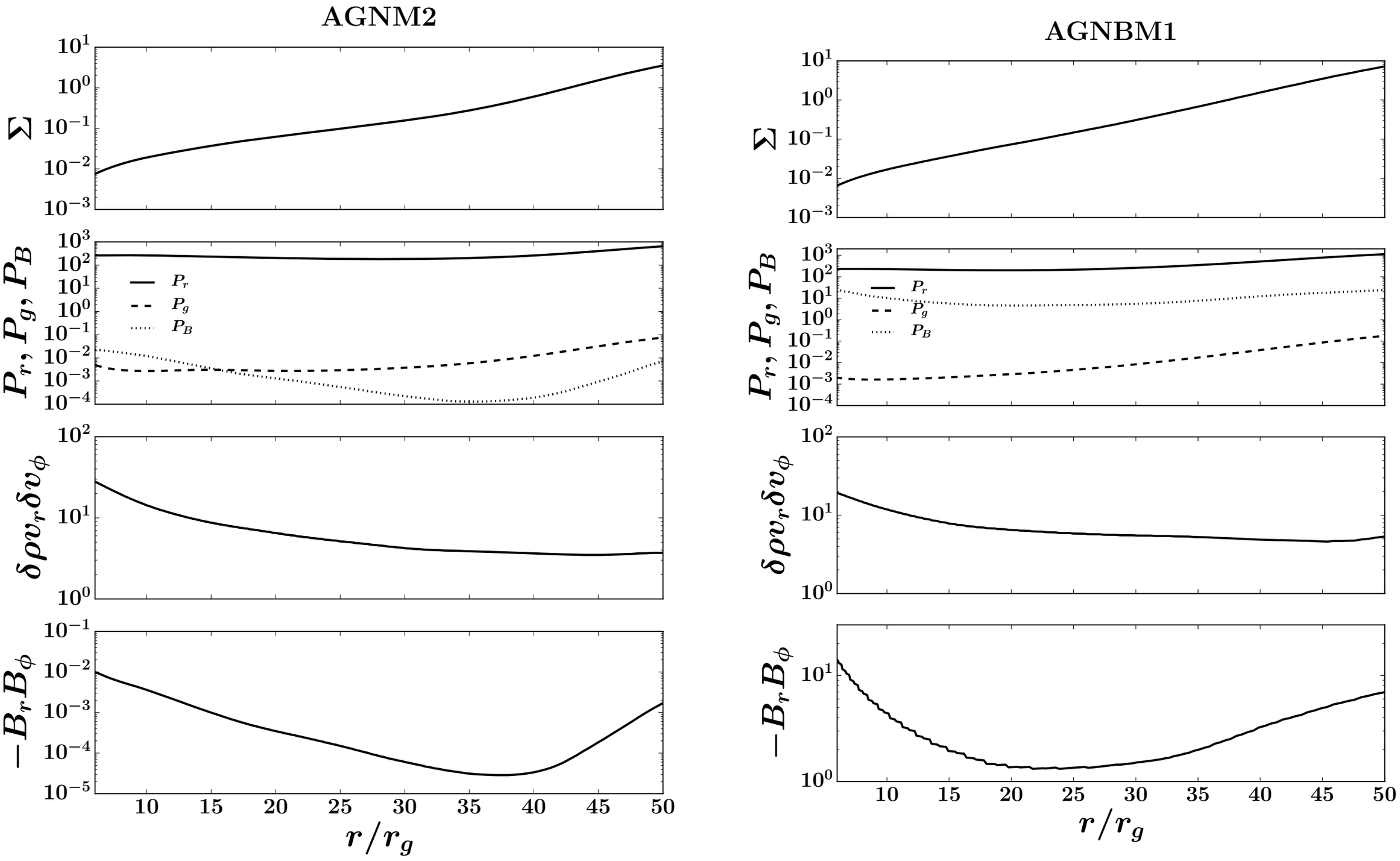
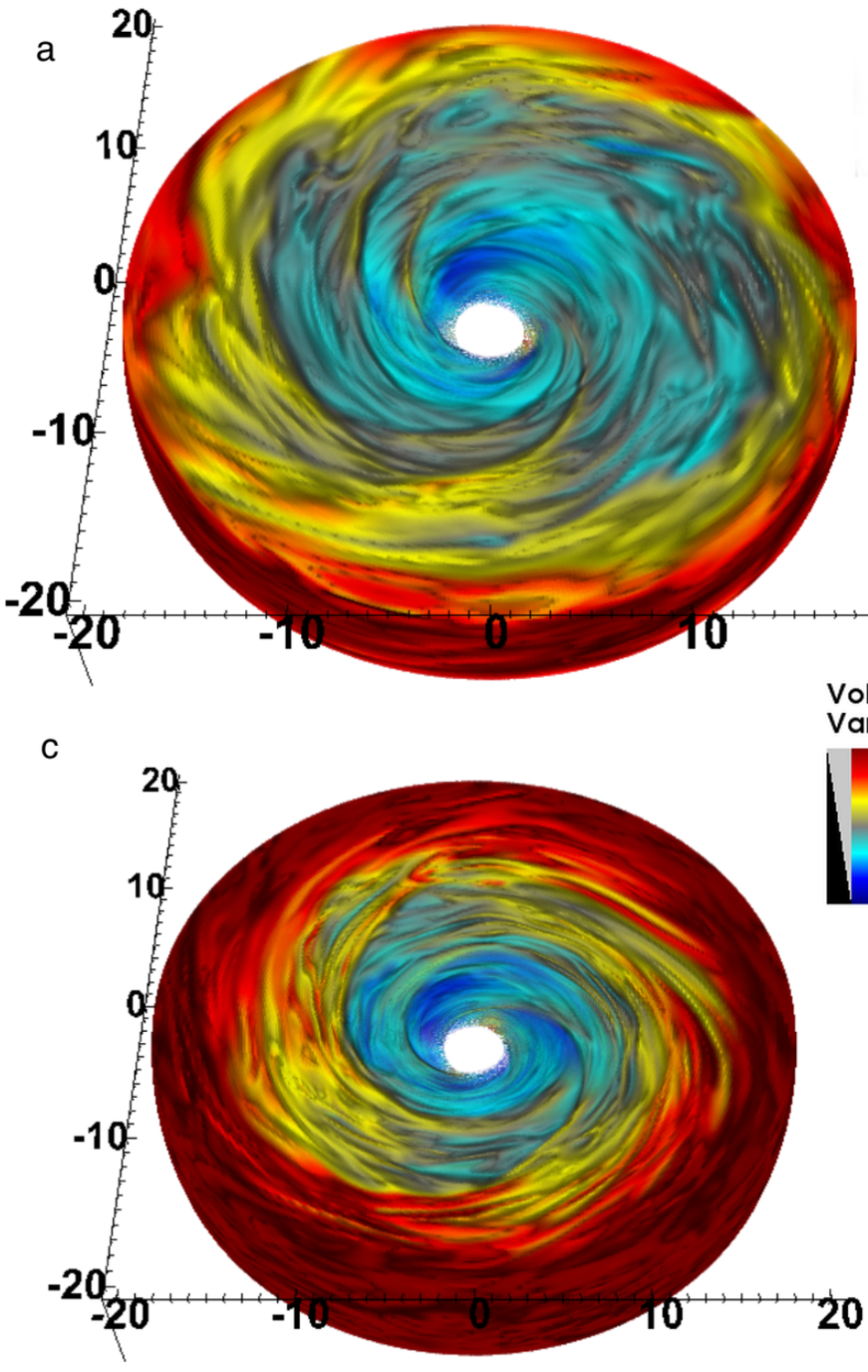


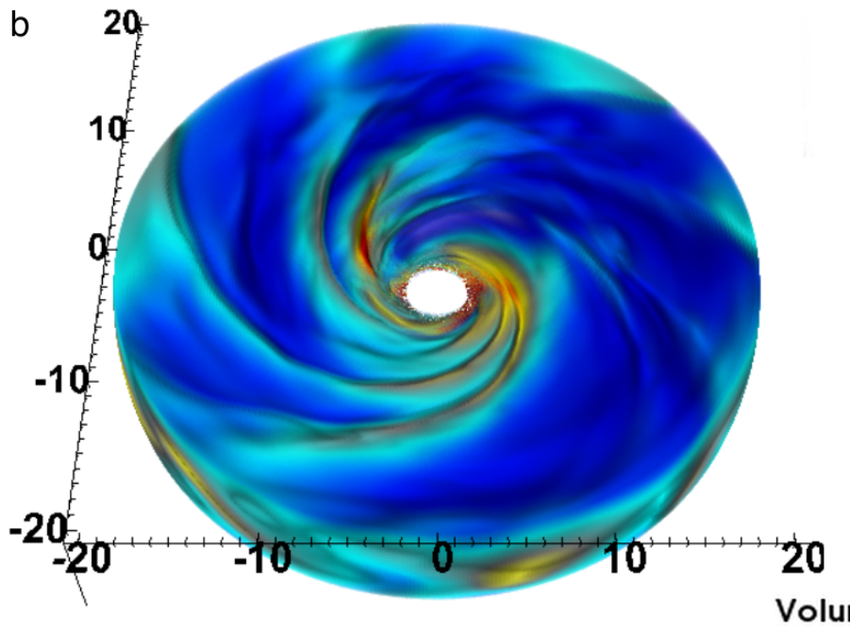
Radial Profiles of the disk



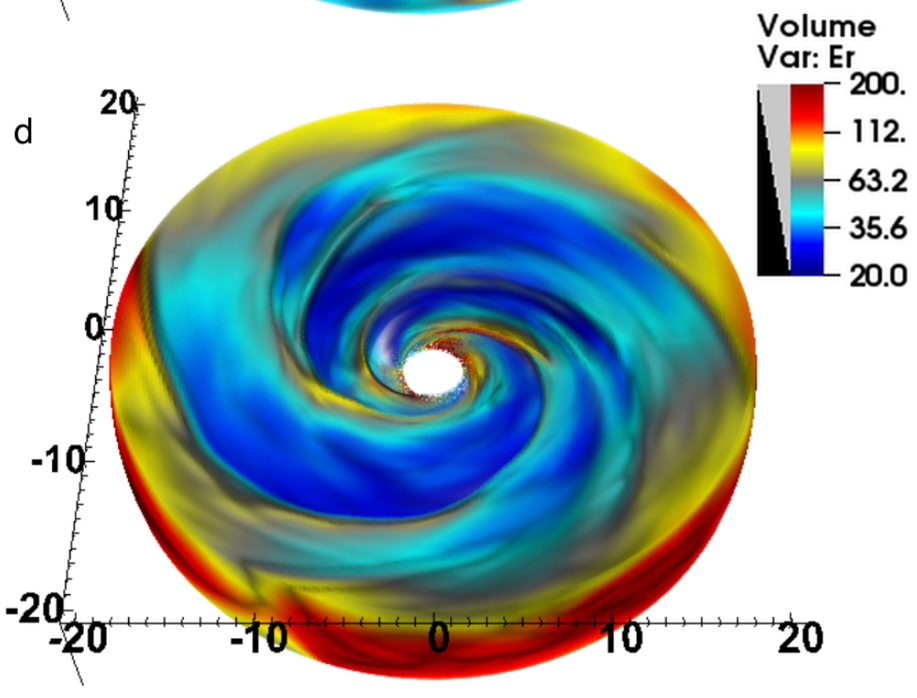
$$\kappa_{\rm es}\Sigma_0 = 5 \times 10^5$$

The Density Waves



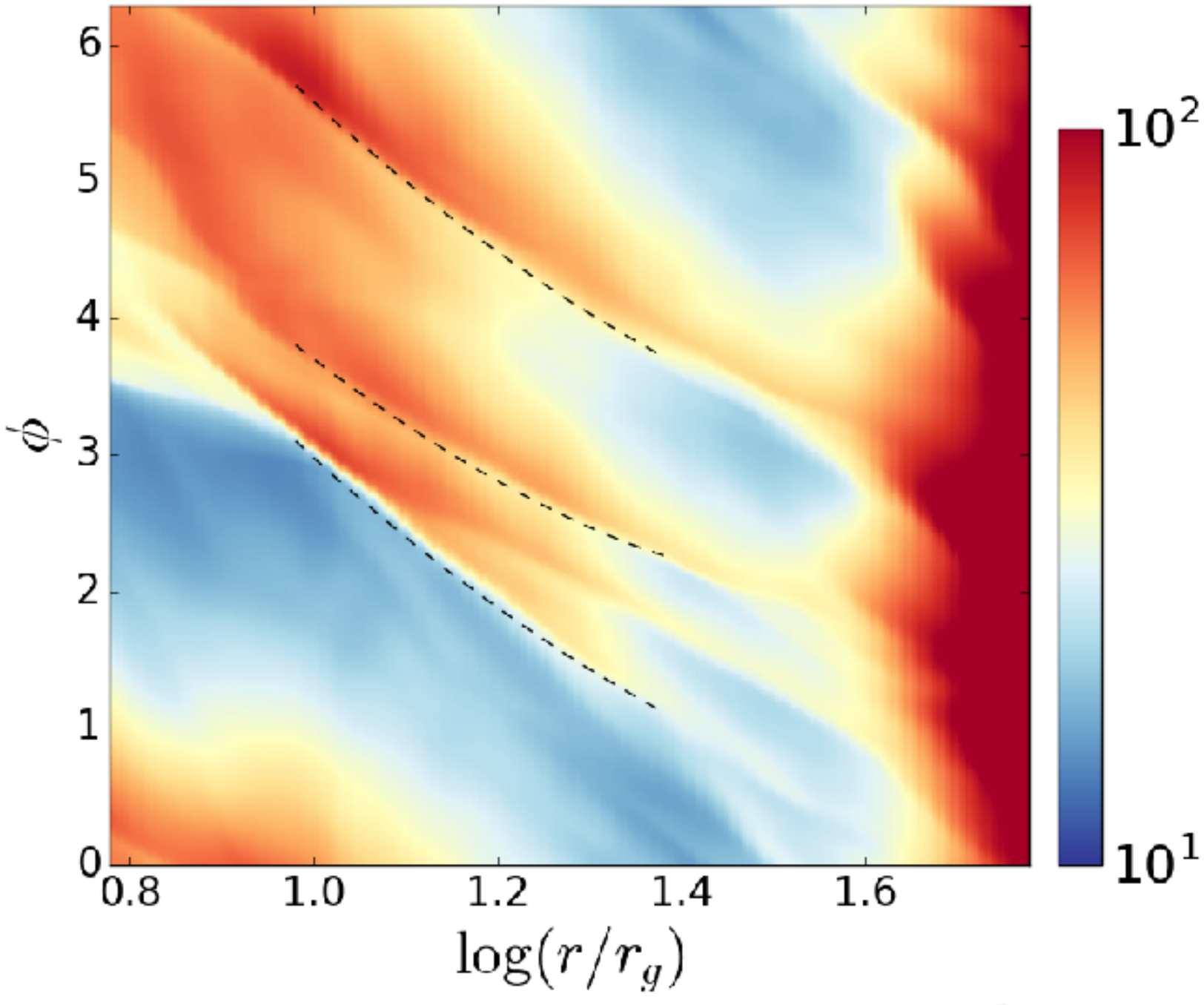


AGNM2



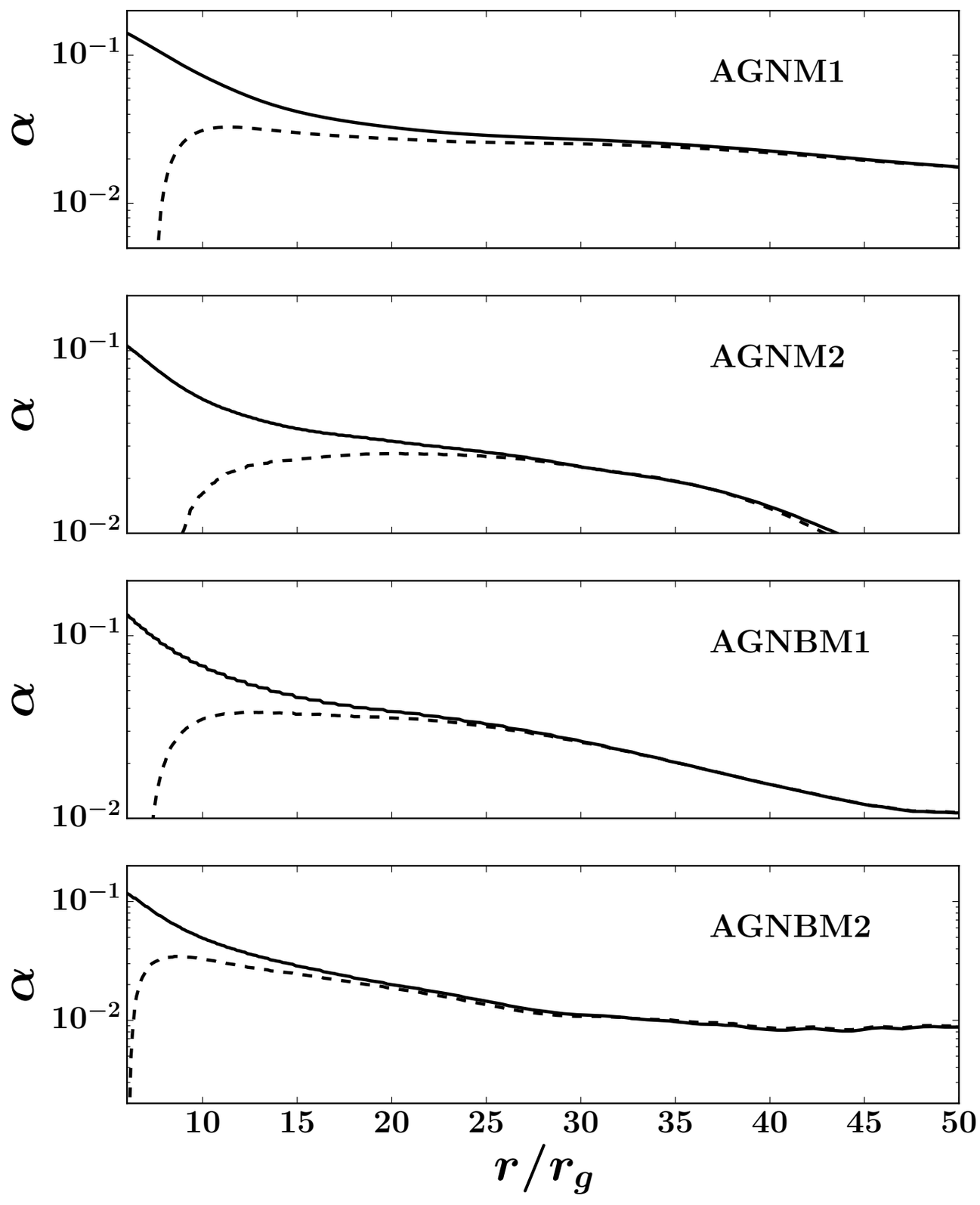
AGNBM1

Positions of the Spiral Shock



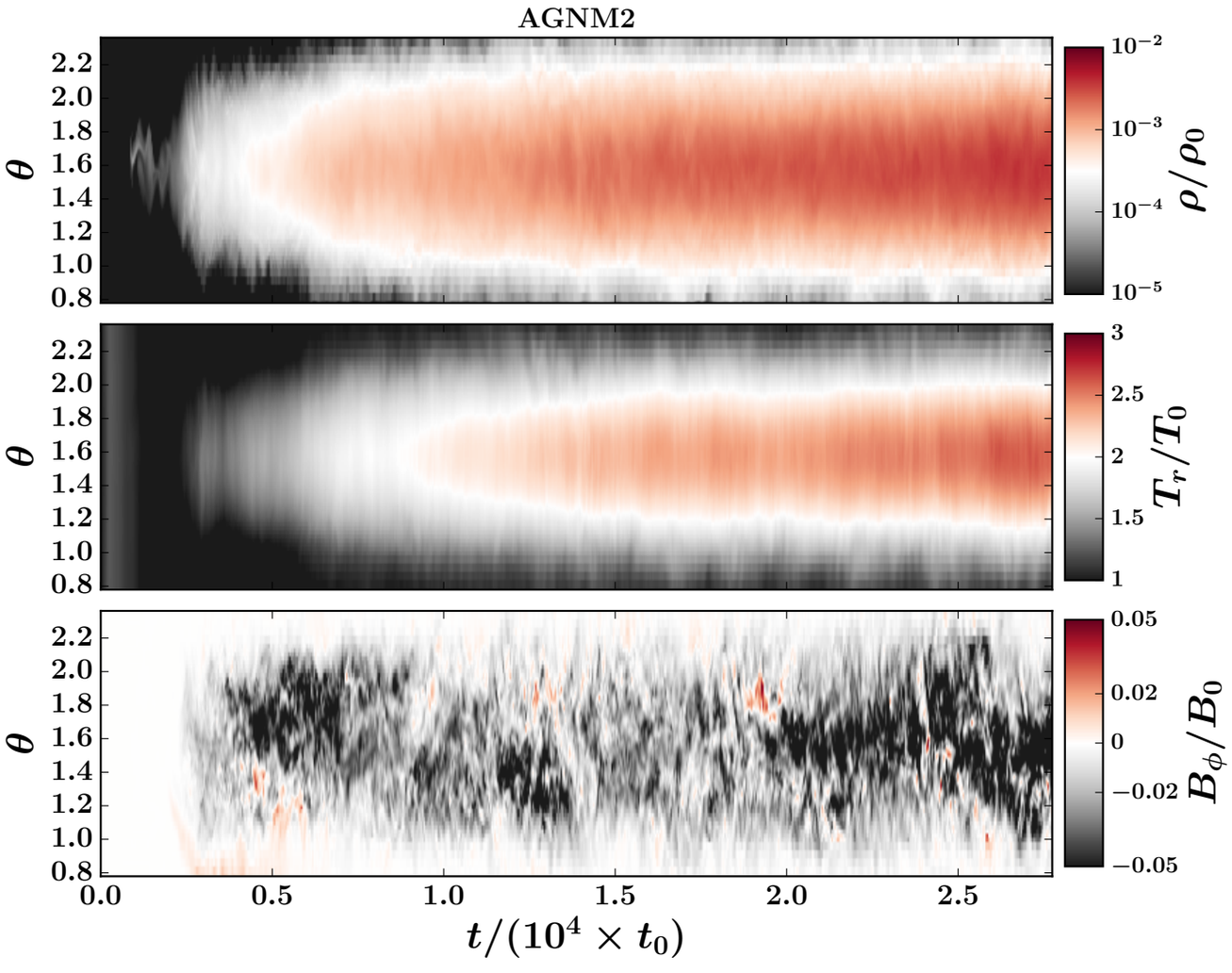
$$d\phi = -\frac{k_r}{m} dr = -\frac{1}{c_s}\sqrt{(\Omega - \Omega_p)^2 - \kappa^2/m^2}\, dr.$$

The Effective Alpha

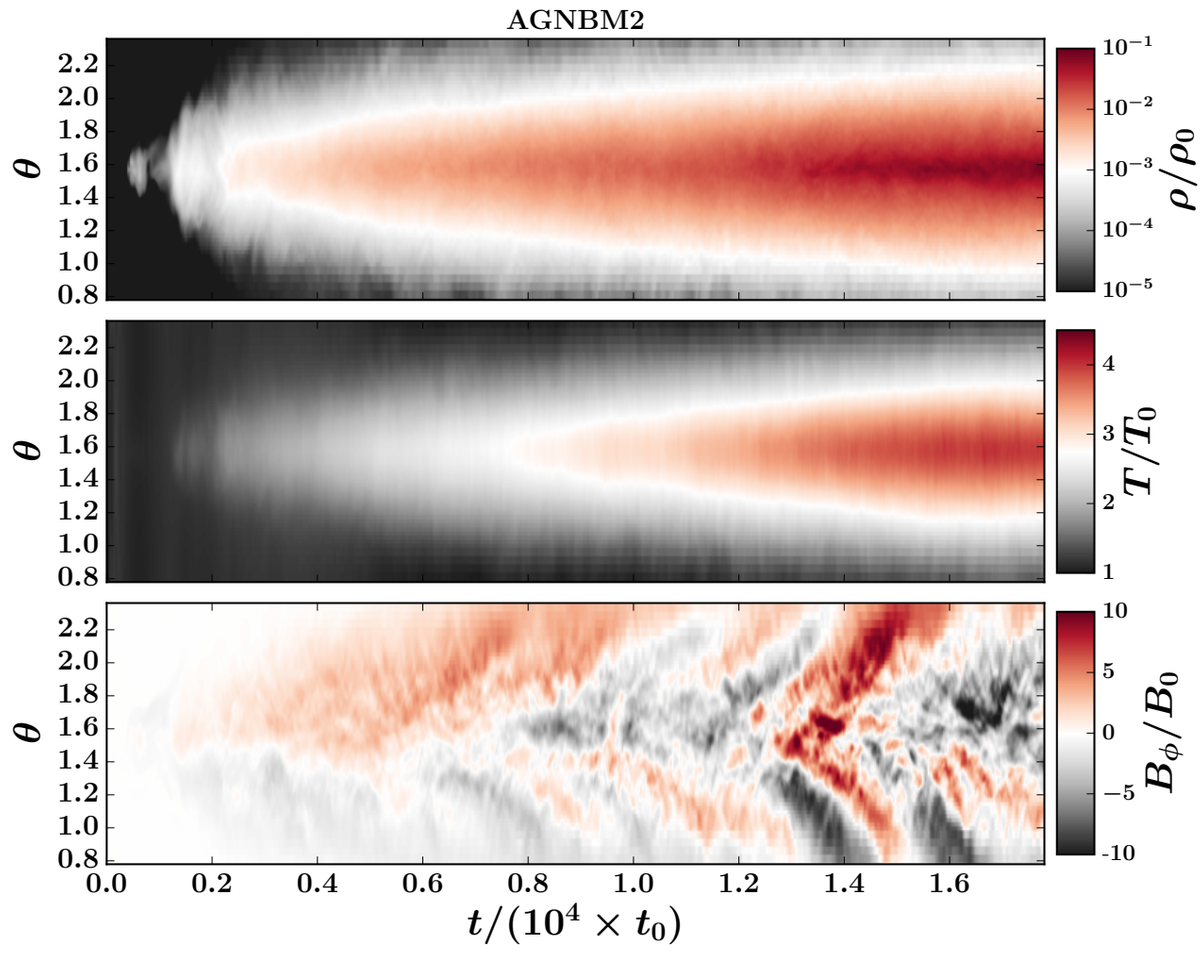


Butterfly Diagram

No Net Vertical Magnetic Flux

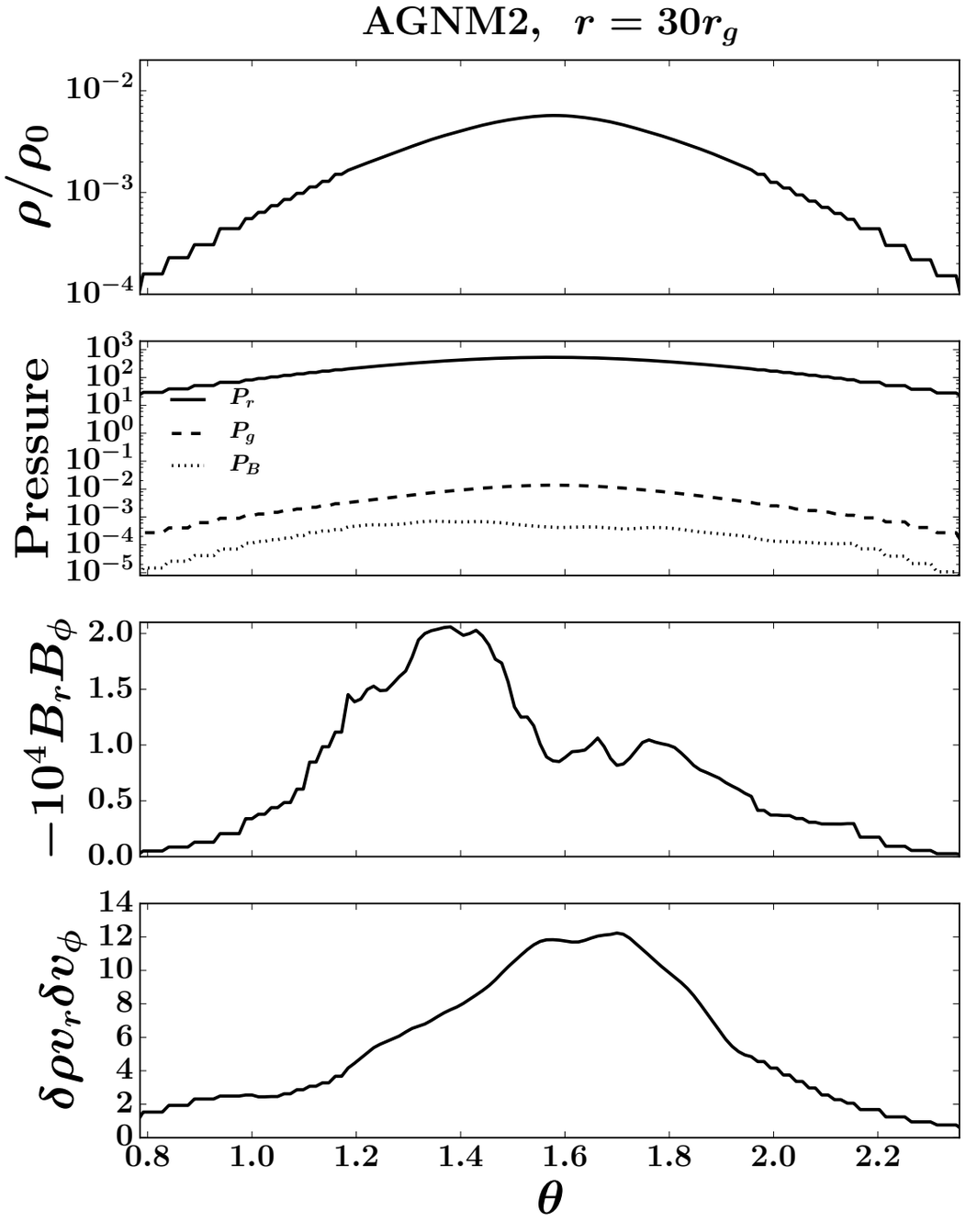


With Net Vertical Magnetic Flux

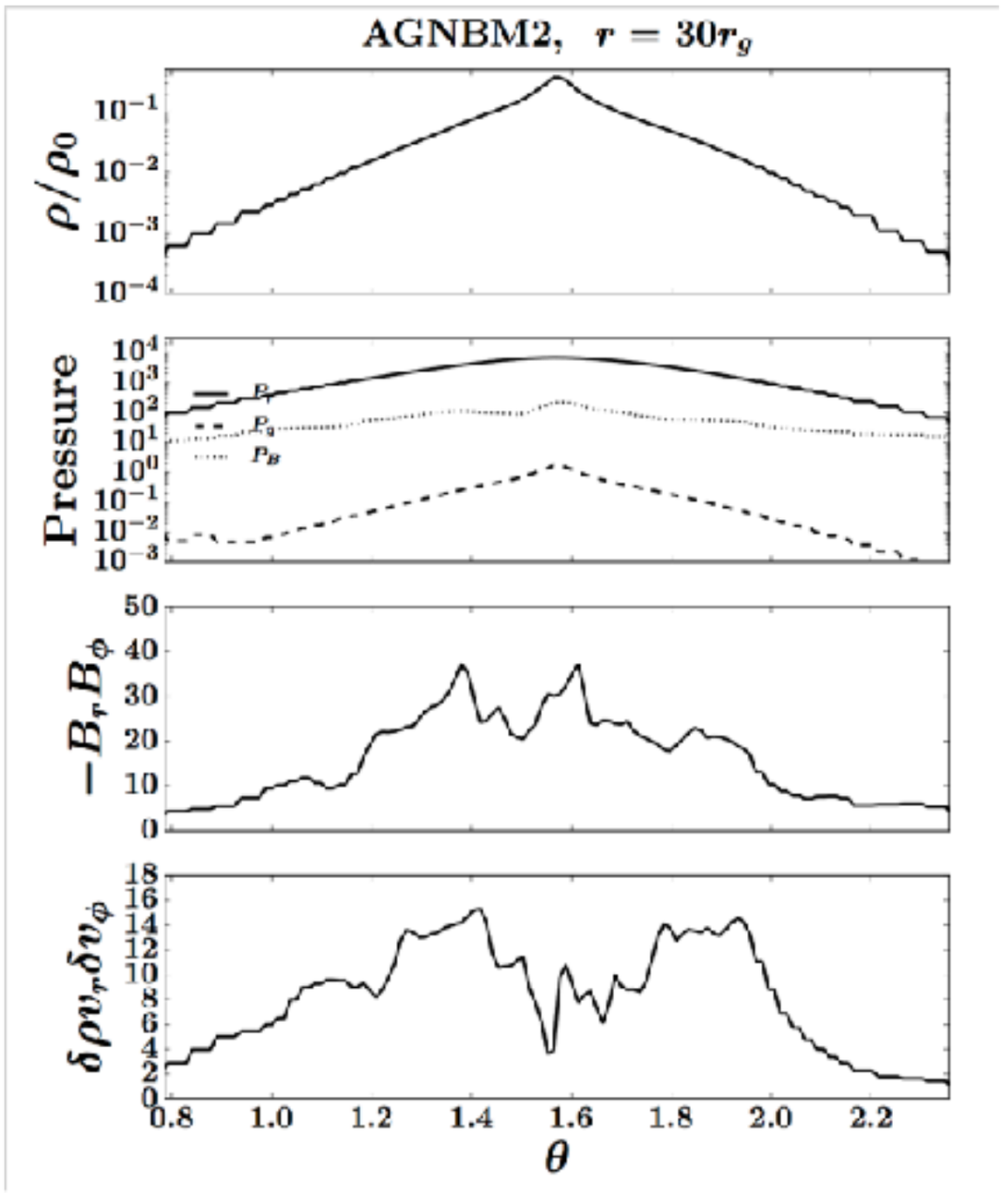


Vertical Disk Structure

No Net Vertical Magnetic Flux



With Net Vertical Magnetic Flux

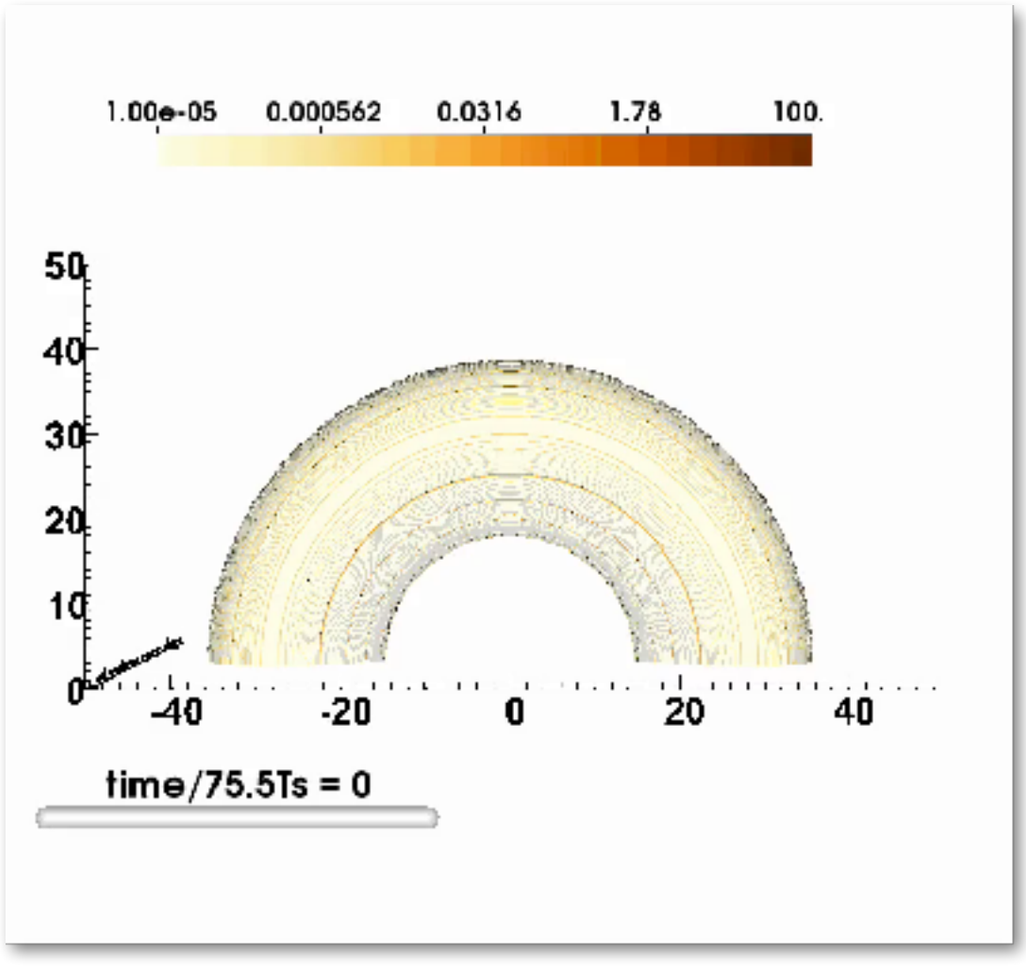


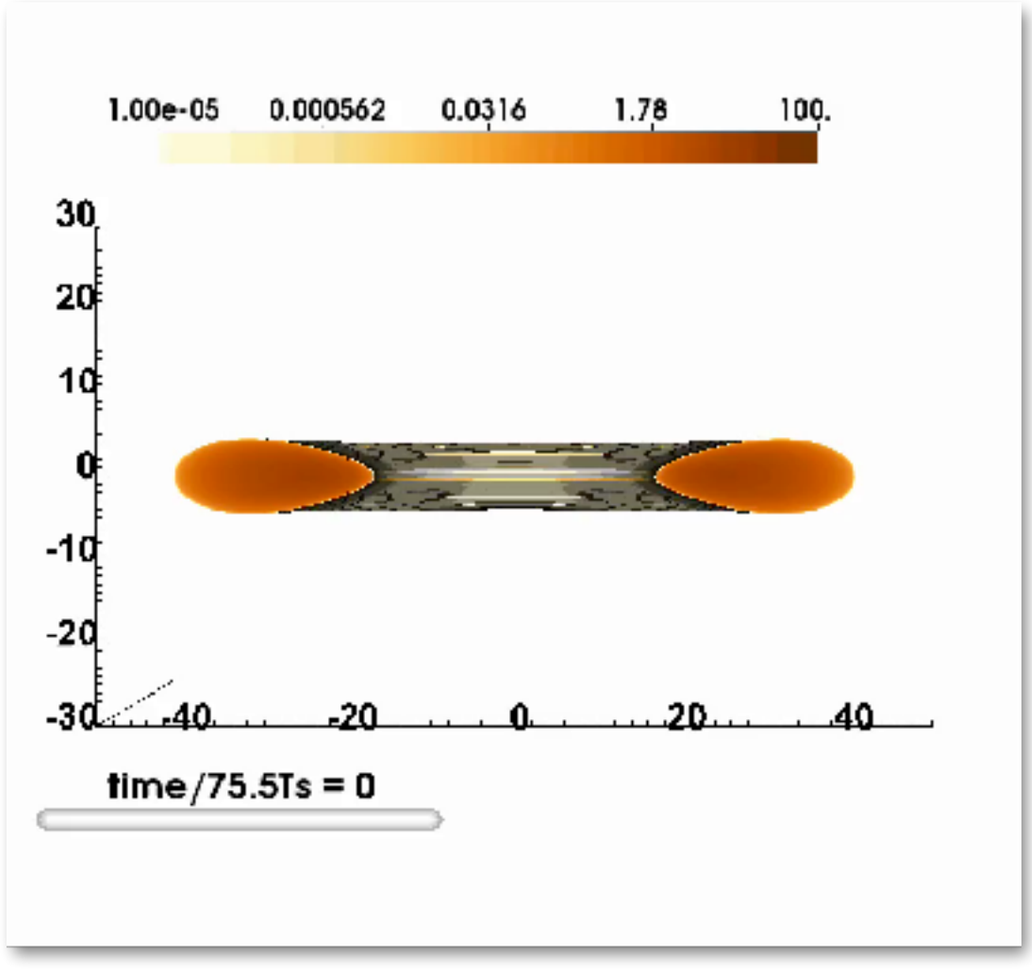
Compare With Stellar Mass Black Holes

~7 solar mass black hole

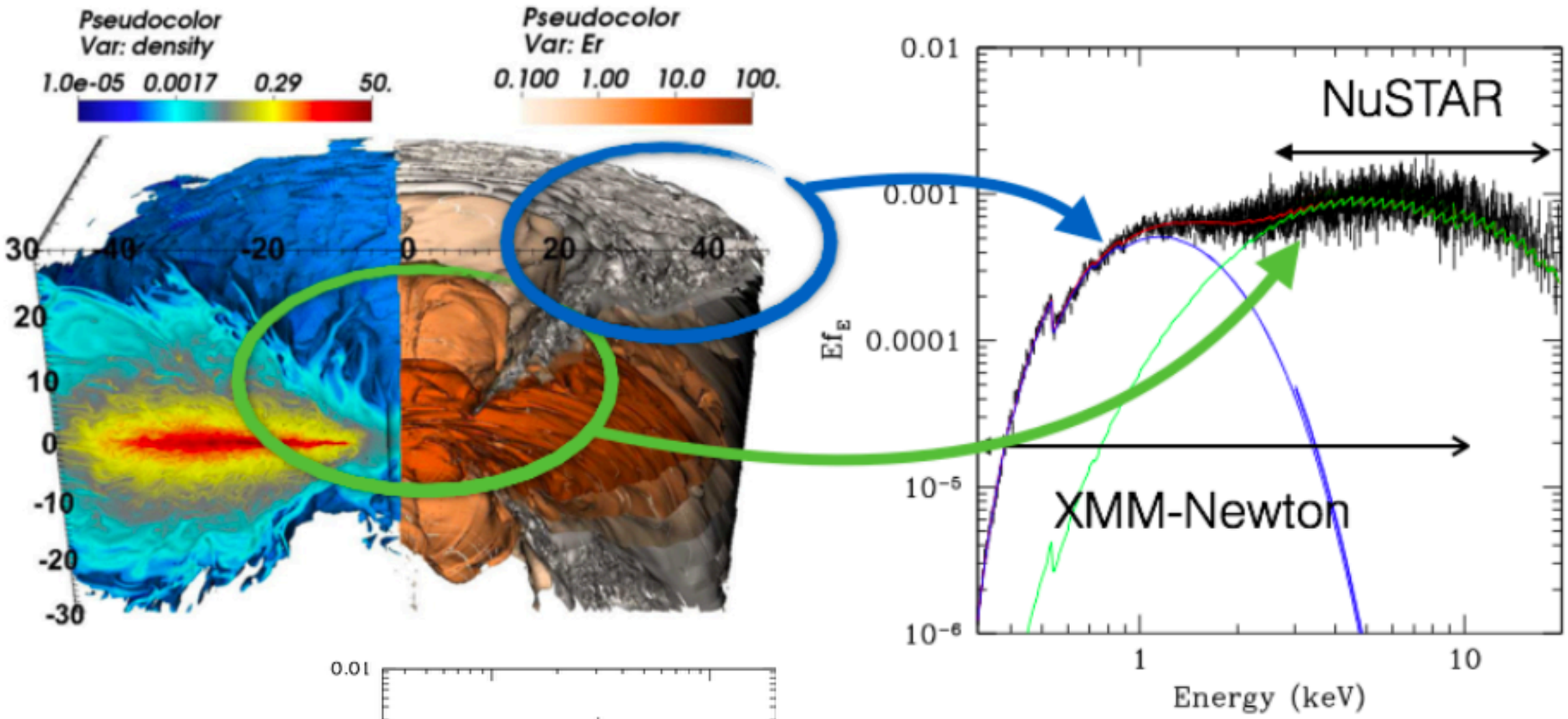
~20 Eddington accretion rate

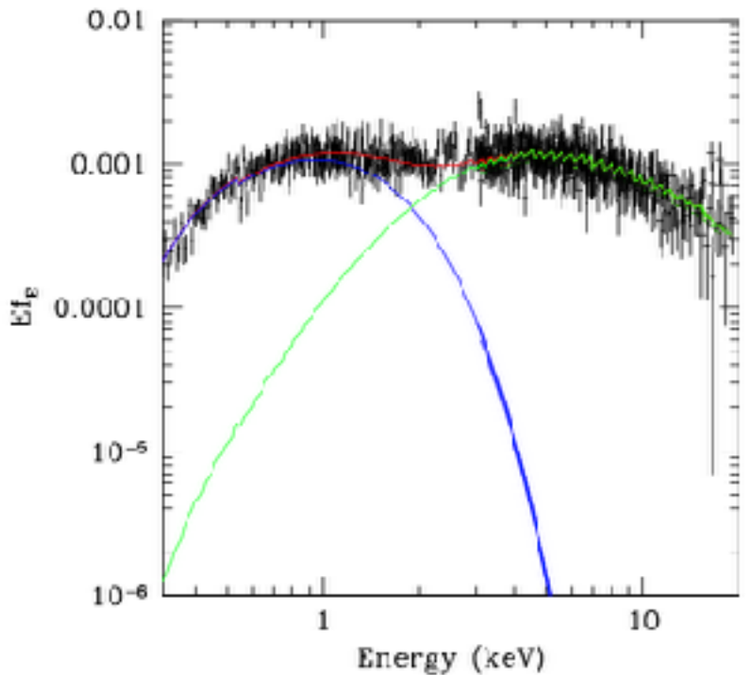
Jiang et al. (2014)





Spectrum?

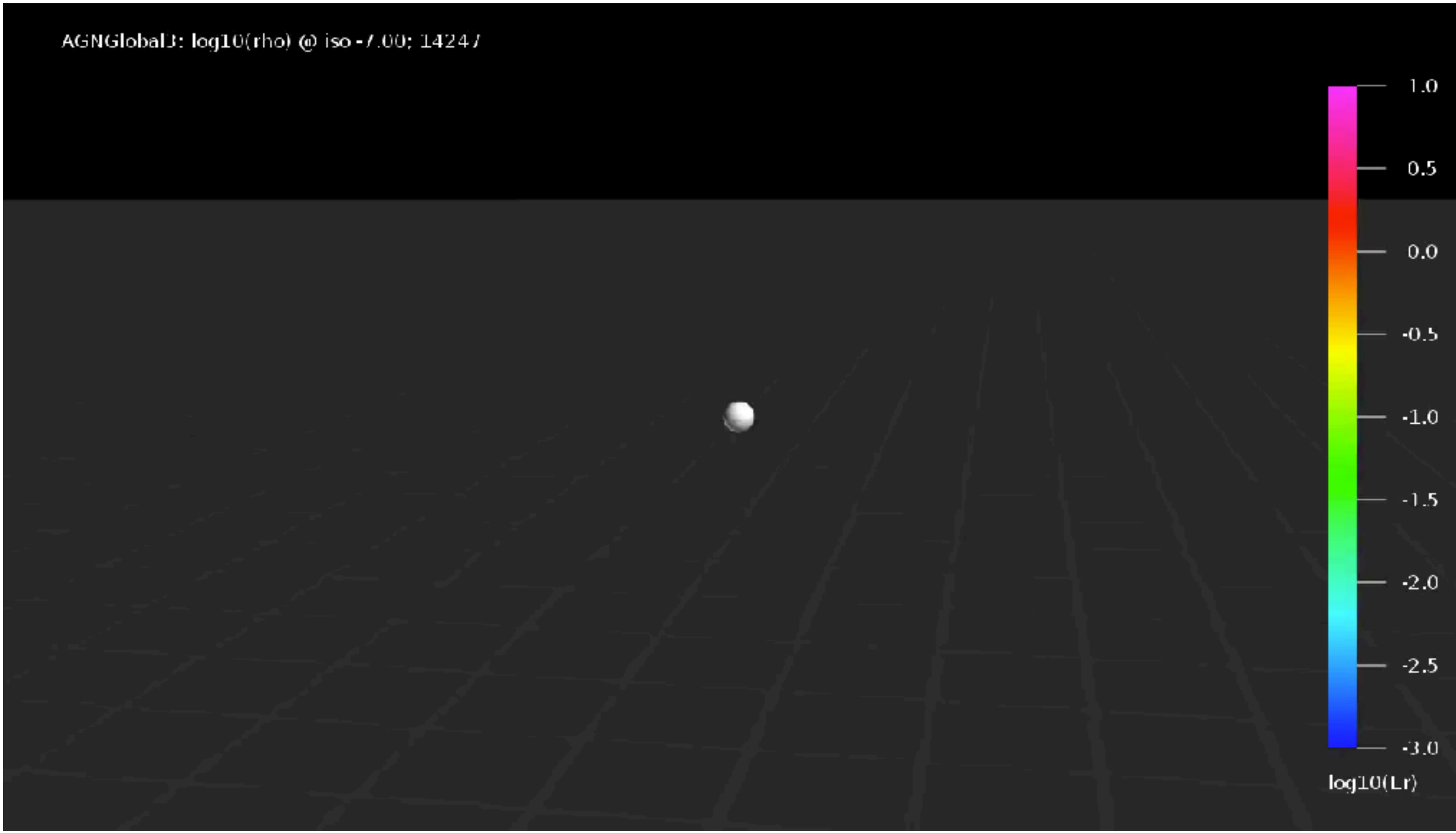




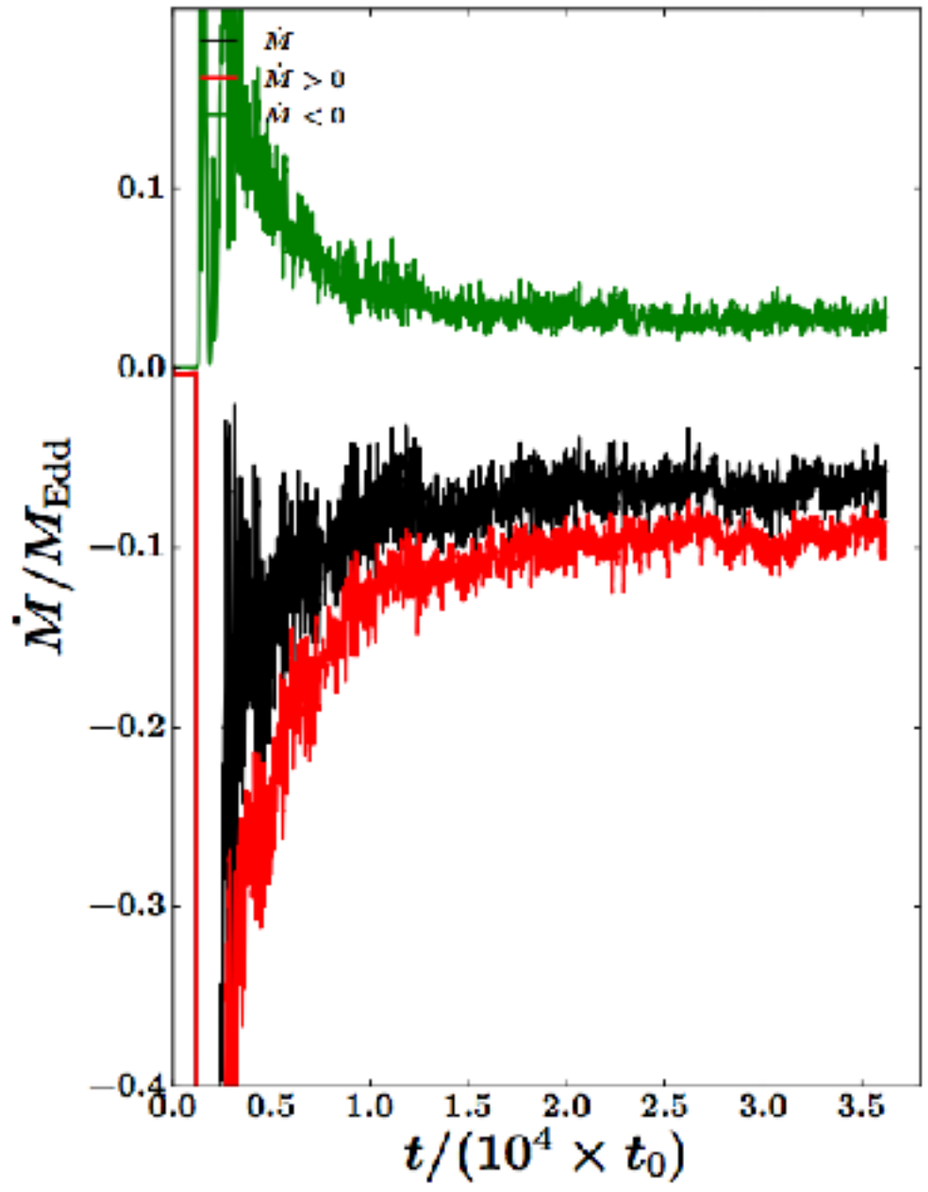
Holl X-1

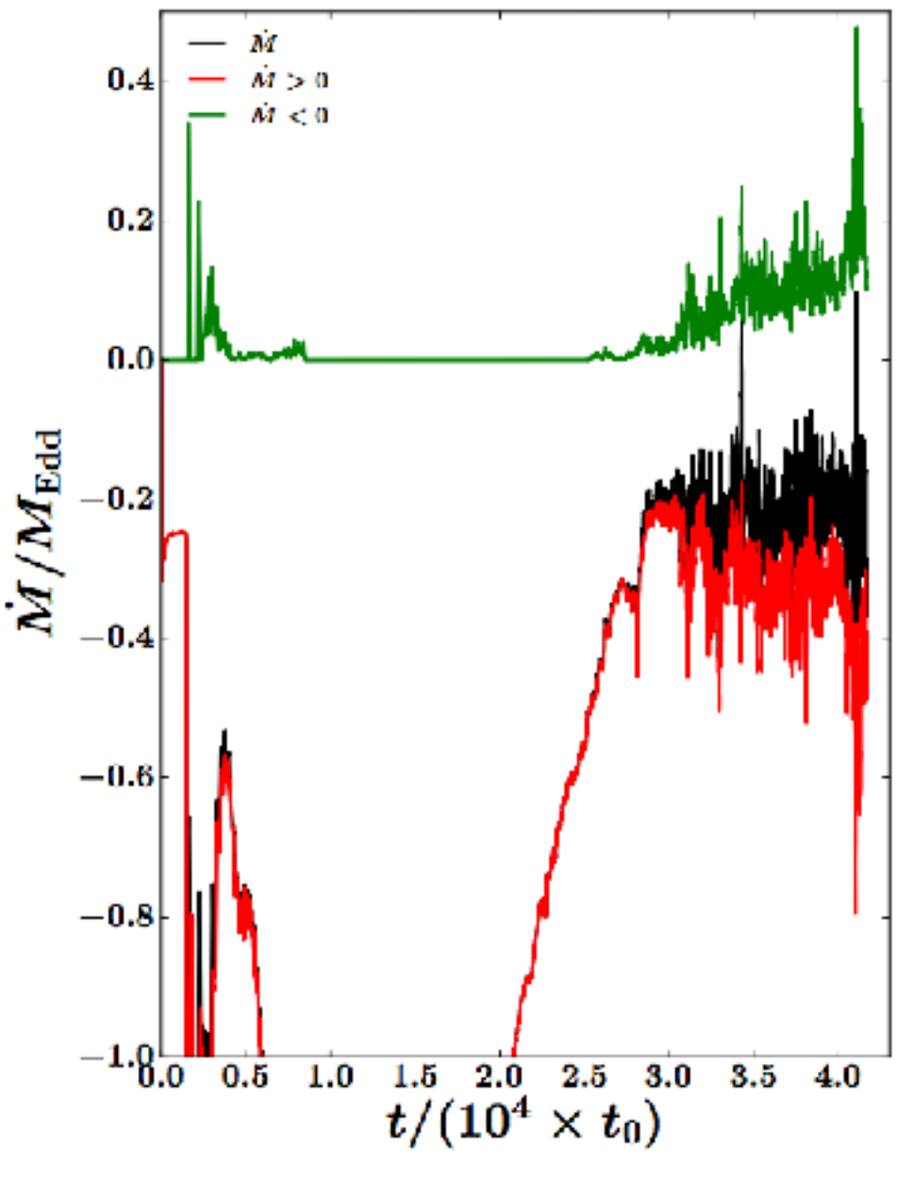
Credit: Matt Middleton
Shane Davis

Sub-Eddington AGN disks

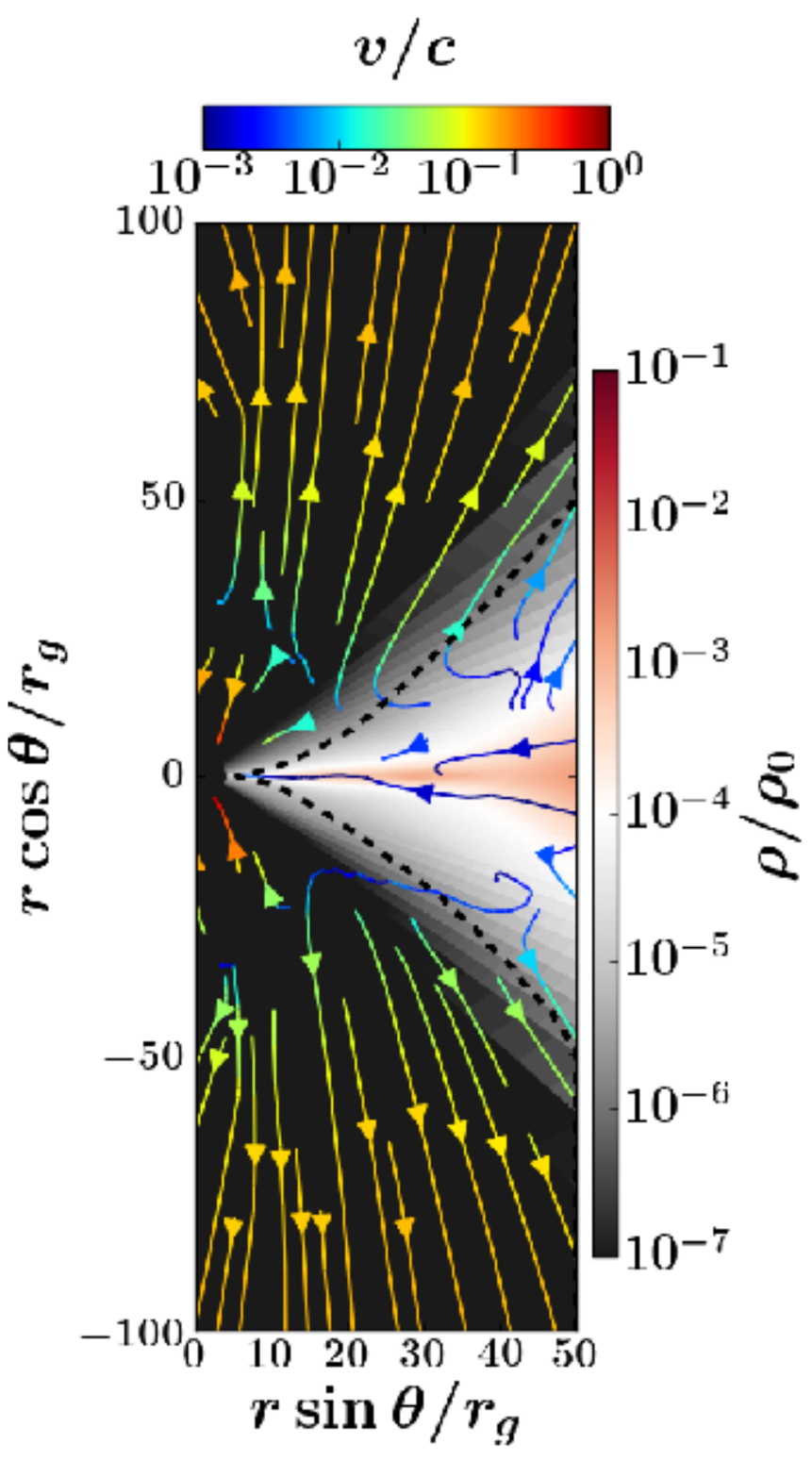


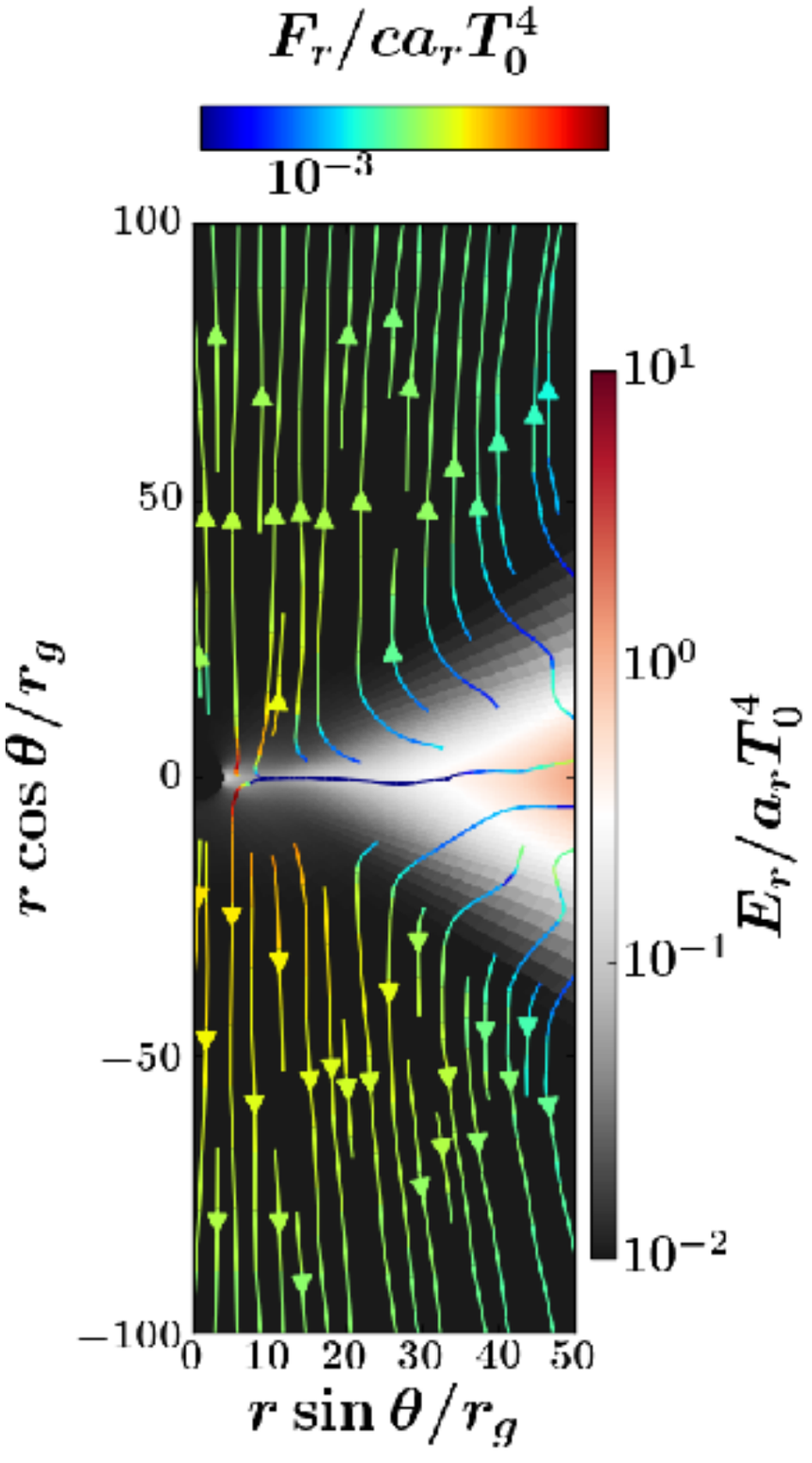
Sub-Eddington AGN disks



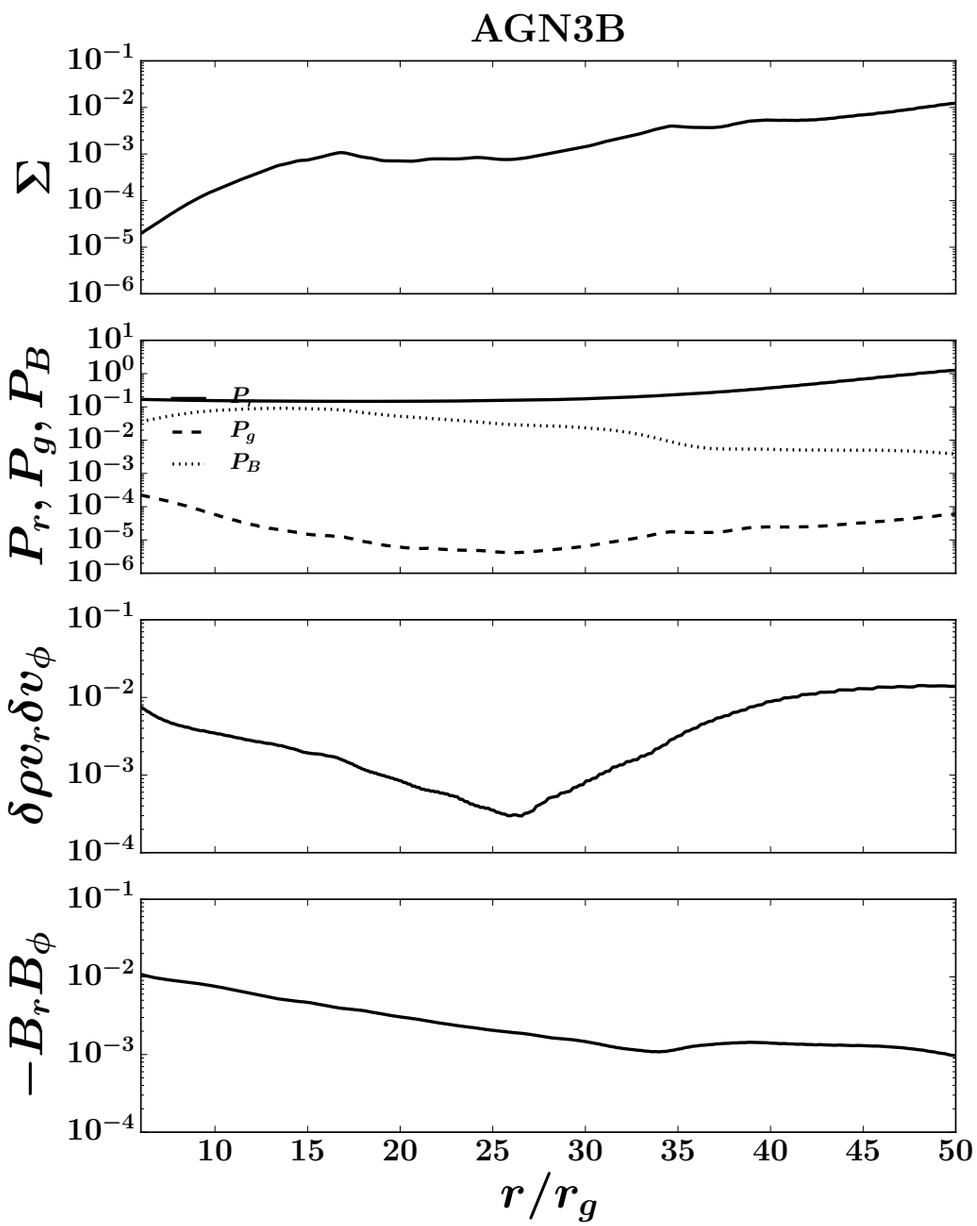


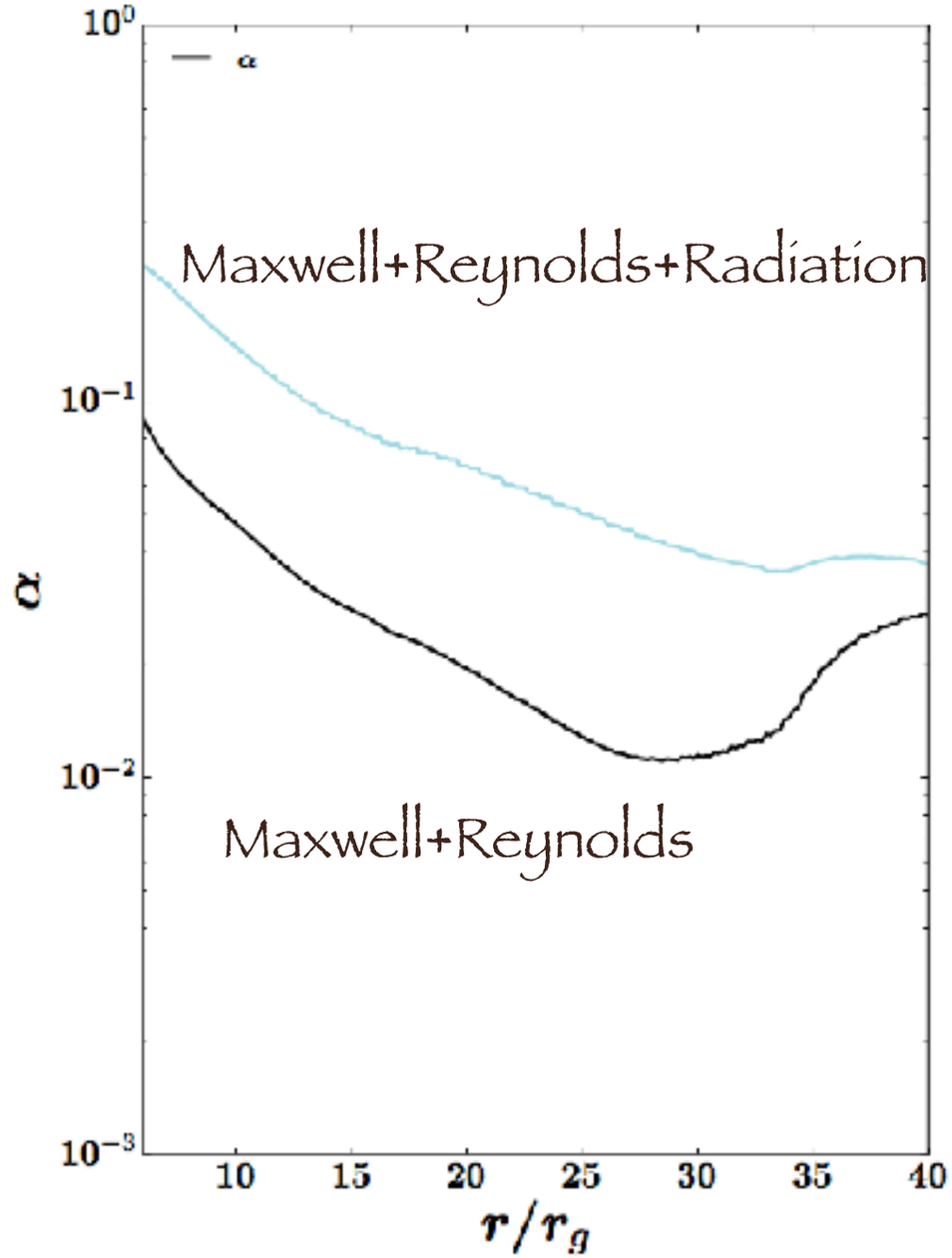
Sub-Eddington AGN disks





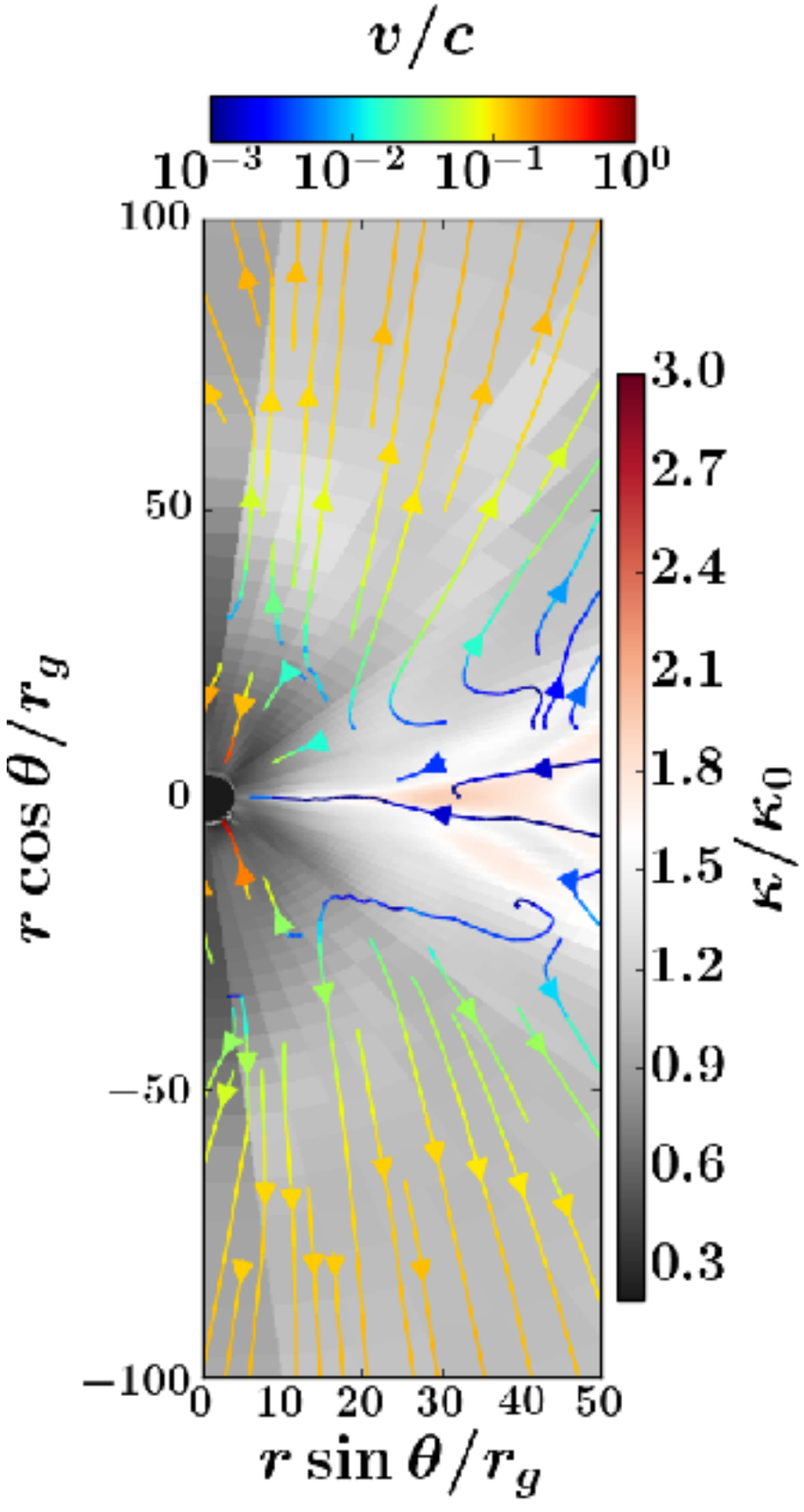
Angular Momentum Transfer





Loeb & Laor (1992)

The Opacity


v/c
10^{-3} 10^{-2} 10^{-1} 10^{0}
100
50
0
−50
−100
0 10 20 30 40 50
$r\sin\theta/r_g$
$r\cos\theta/r_g$
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
κ/κ_0

Future Work

- AGN spectra for different accretion rates and black hole mass
- Reverberation mapping based on Simulation Data
- Signature of Continuum Radiation Driven Outflow