Convection, MRI, and Magnetic Elevation in High Luminosity Accretion Disks Around Supermassive Black Holes

Omer Blaes
(UCSB)

with Yan-Fei Jiang 姜燕飞 (Flatiron Insitute),
Ish Kaul (UCSB),
Lizhong Zhang 张力中 (IAS)

Turbulence in the Universe, KITP Santa Barbara, February 2024

Reverberation mapping campaigns show that luminous AGN are probably powered by optically thick accretion in which accretion power is thermalized into radiation at some level

$$4\pi r^2 \sigma T_{\mathrm{e}}^4 \sim \frac{GM\dot{M}}{r}$$

$$T_{\mathrm{e}} \sim \left(\frac{GM\dot{M}}{4\pi r^3 \sigma}\right)^{1/4} \sim 6\times 10^5\ \mathrm{K}\left(\frac{M}{10^8 M_\odot}\right)^{-1/4}\left(\frac{\dot{M}}{\eta \dot{M}_{\mathrm{Edd}}}\right)^{1/4}\left(\frac{r}{r_{\mathrm{g}}}\right)^{-3/4}$$

cf. standard (Newtonian) disk theory:

$$T_{\mathrm{e}} \sim \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma}\right)^{1/4}\left(1-\sqrt{\frac{r_{\mathrm{in}}}{r}}+\frac{4\pi r_{\mathrm{in}}^2 H_{\mathrm{in}} \tau_{r\phi,\mathrm{in}}}{\dot{M}\sqrt{GMr}}\right)^{1/4}$$

$$T_{\mathrm{e}} \propto r^{-3/4} \Leftrightarrow F_\nu \propto \nu^{1/3}$$

But there are big problems with disk theory vis a vis observations…

- UV spectra have a quasi-universal shape with a break to a power-law at $1000\,\text{Å}$ (near the Lyman limit), nothing like what standard accretion disk theory predicts.
- Microlensing and reverberation mapping place the optical emission radius to be about a factor 3 larger than standard accretion disk theory predicts.
- Observed variability occurs on very rapid time scales compared to standard disk theory, the most extreme manifestation being so-called Changing Look Quasars.

Also, the standard Shakura-Sunyaev-based theory is itself inconsistent because of thermal and viscous instabilities.

Key Ingredients Not Addressed in Standard Model

- Disk winds (Proga, Stone & Kallman 2000; Laor & Davis 2014)
- FUV opacities in a radiation pressure dominated environment (Jiang, Davis & Stone 2016; Jiang & Blaes 2020)
- Magnetic pressure support, even in a SANE flow (Pariev, Blackman & Boldyrev 2003; Begelman & Pringle 2007; Begelman & Silk 2017; Dexter & Begelman 2019; Mishra et al. 2020; Begelman & Armitage 2023)

Local Conditions in a Luminous AGN Accretion Flow

$$\dot{M} = (2\pi r)(2H)\rho v$$

$$v = \alpha \left(\frac{H}{r}\right)^2 \left(\frac{GM}{r}\right)^{1/2}$$

Defines alpha!

$$\rho \;=\; 2\times 10^{-13}\text{g cm}^{-3}\alpha^{-1}\left(\frac{M}{10^8 M_\odot}\right)^{-1}\left(\frac{r}{r_\text{g}}\right)^{-3/2}\left(\frac{H}{r}\right)^{-3}\left(\frac{\dot{M}}{\eta \dot{M}_\text{Edd}}\right)$$

$$L(r) \sim f_\text{rad}\frac{GM\dot{M}\Delta r}{r^2}$$

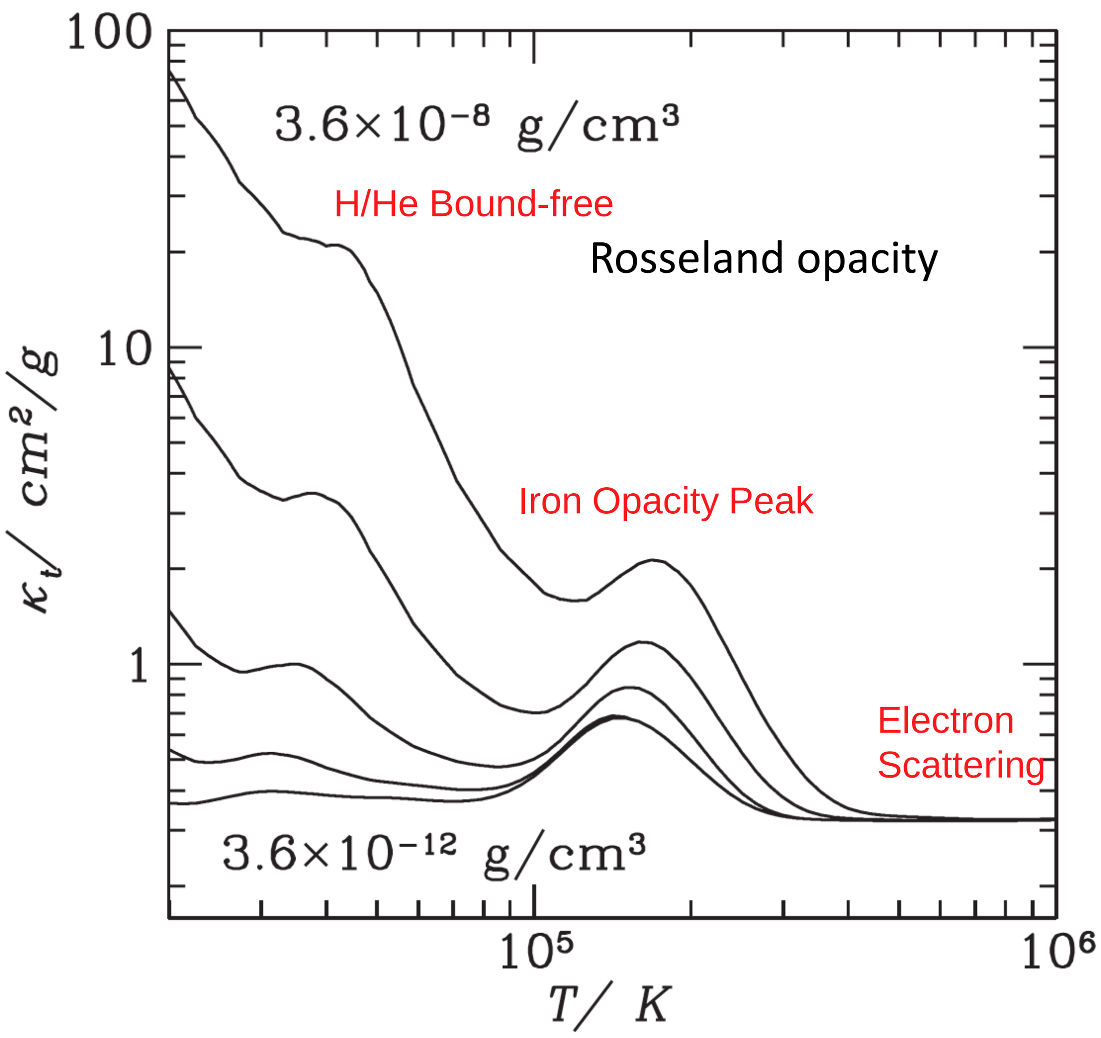
$$L(r) = 4\pi r\Delta r\frac{acT^4}{3\kappa\rho H}$$

IF diffusive transport

$$T \;=\; 5\times 10^5\text{K}\;\alpha^{-1/4}\left(\frac{M}{10^8 M_\odot}\right)^{-1/4} f_\text{rad}^{1/4}\left(\frac{r}{r_\text{g}}\right)^{-7/8}\left(\frac{H}{r}\right)^{-1/2}\left(\frac{\kappa}{\kappa_\text{T}}\right)^{1/4}\left(\frac{\dot{M}}{\eta \dot{M}_\text{Edd}}\right)^{1/2}$$

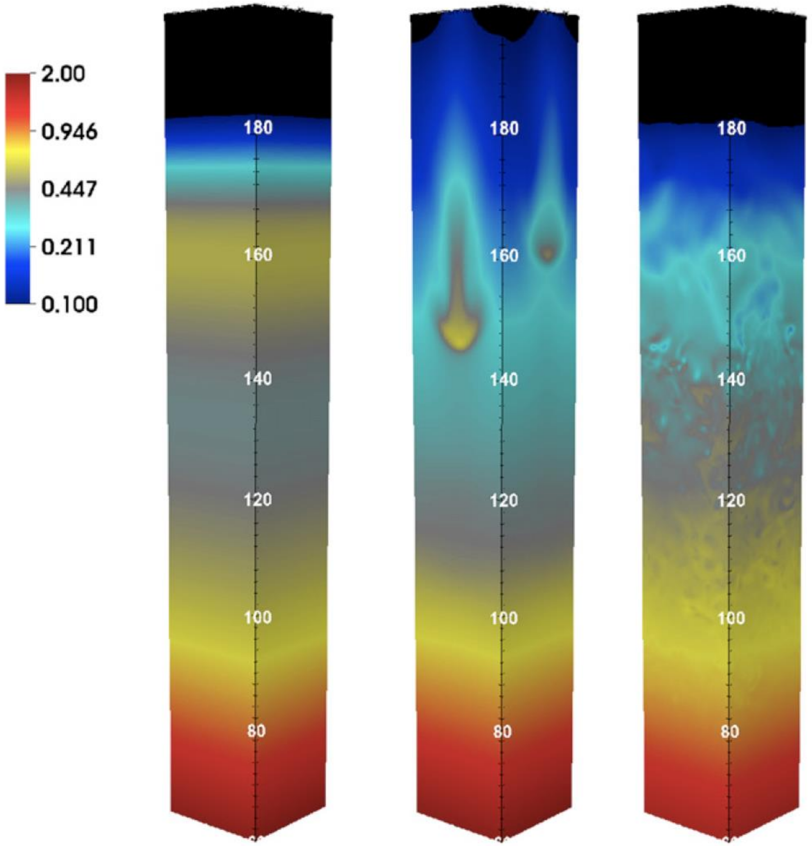
$$\frac{P_\text{rad}}{P_\text{gas}} \;=\; 1\times 10^7\alpha^{1/4}\left(\frac{M}{10^8 M_\odot}\right)^{1/4} f_\text{rad}^{3/4}\left(\frac{r}{r_\text{g}}\right)^{-9/8}\left(\frac{H}{r}\right)^{3/2}\left(\frac{\kappa}{\kappa_\text{T}}\right)^{3/4}\left(\frac{\dot{M}}{\eta \dot{M}_\text{Edd}}\right)^{1/2}$$

The Iron Opacity Peak in FUV Temperature Plasmas

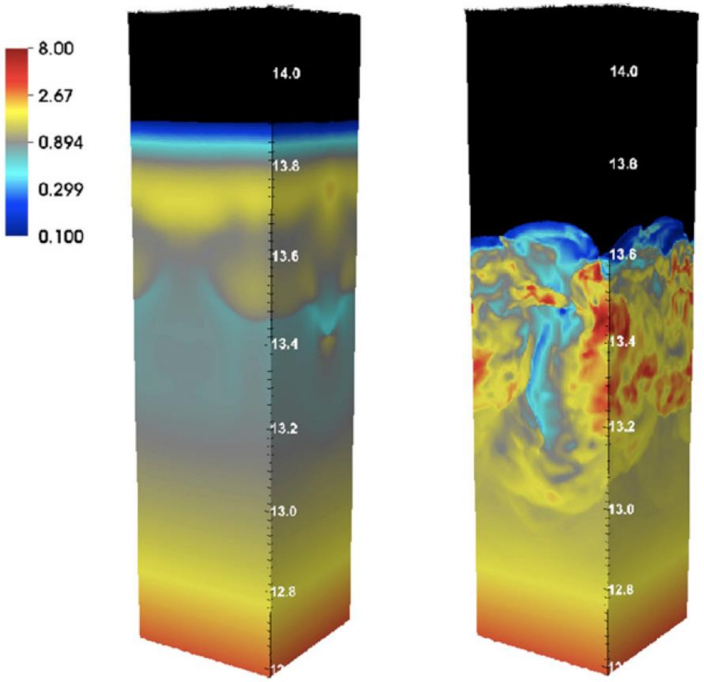


-Jiang et al. (2015)

Iron Opacity Effects in Massive Stars



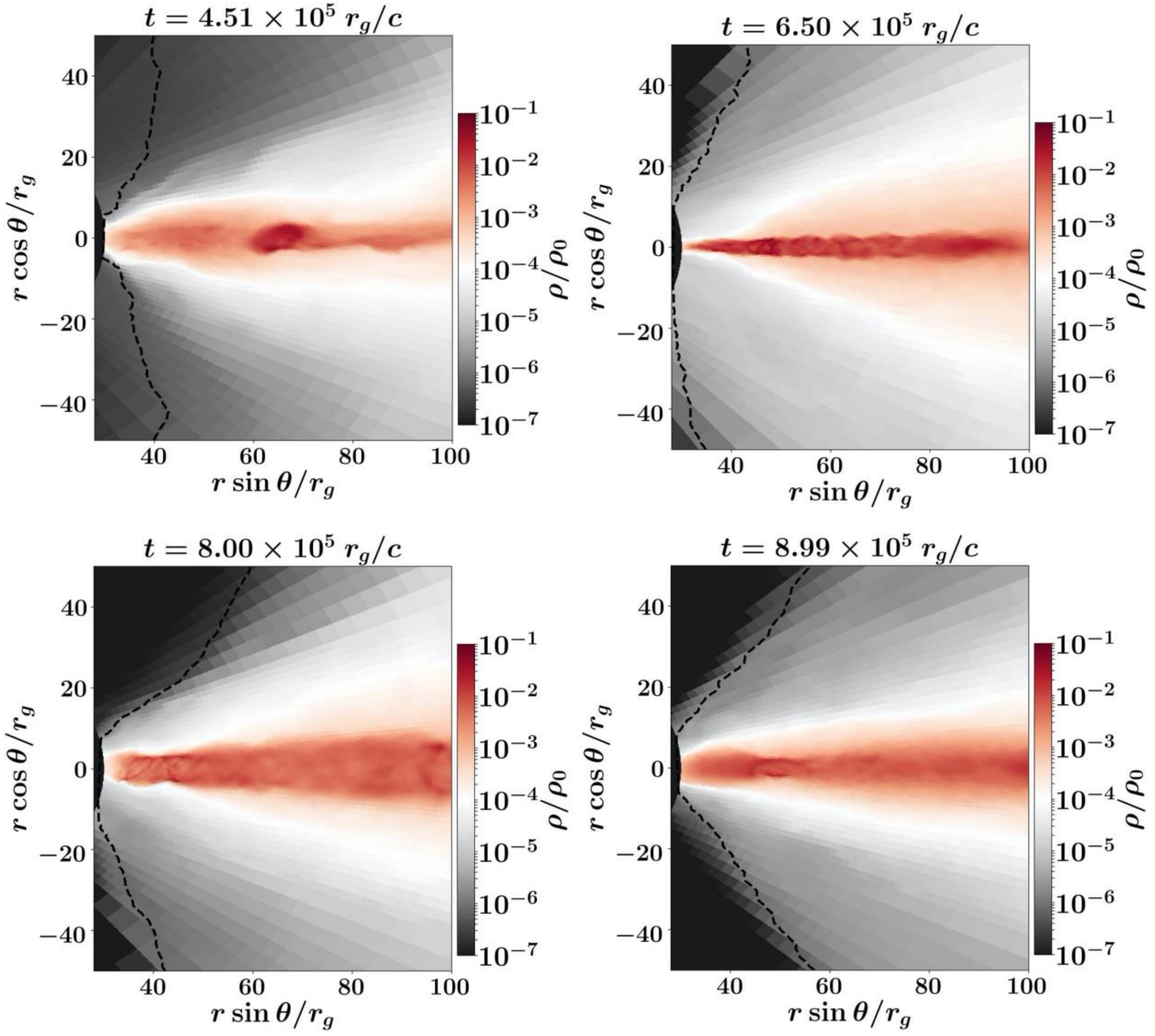
Slow photon diffusion:
density inversion wiped out
and convection is efficient.



Rapid photon diffusion:
strong turbulence results in
porous medium. Density inversion is
maintained in time/space average.

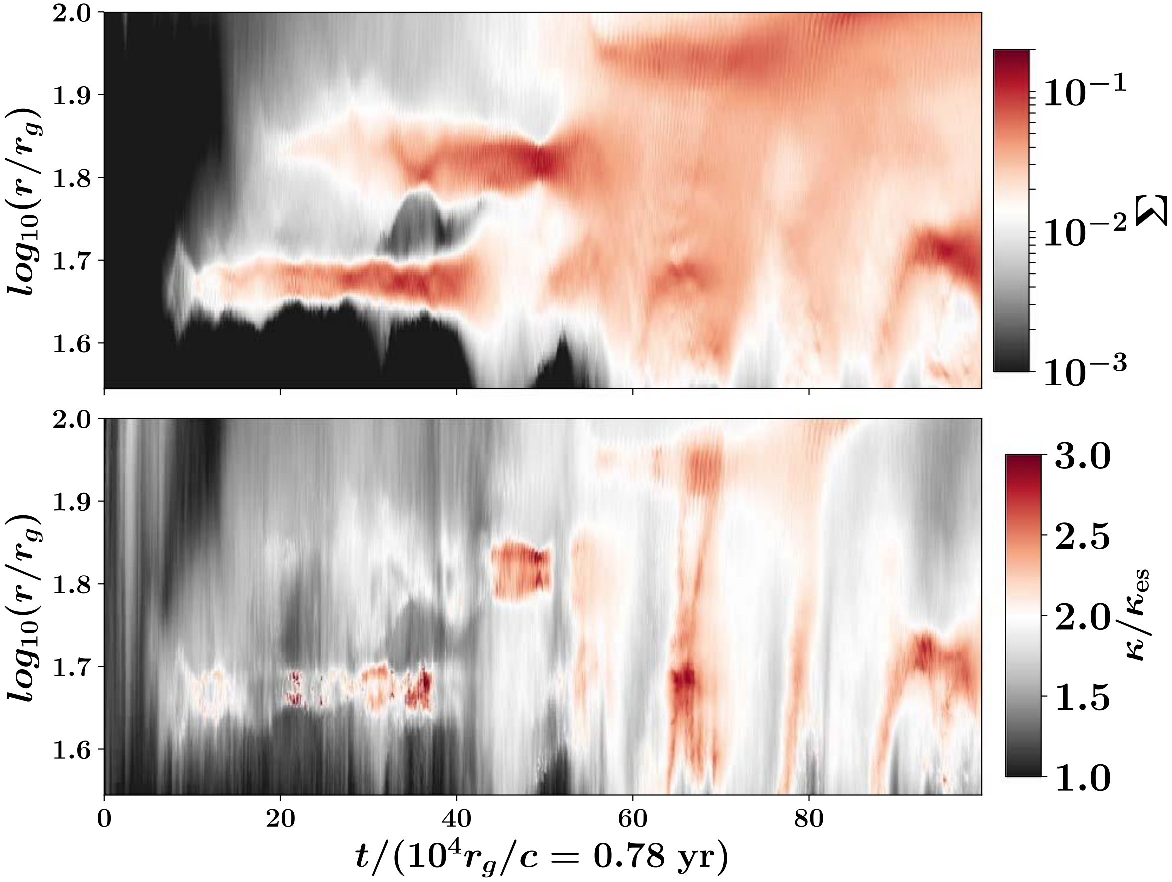
-Jiang et al. (2015)

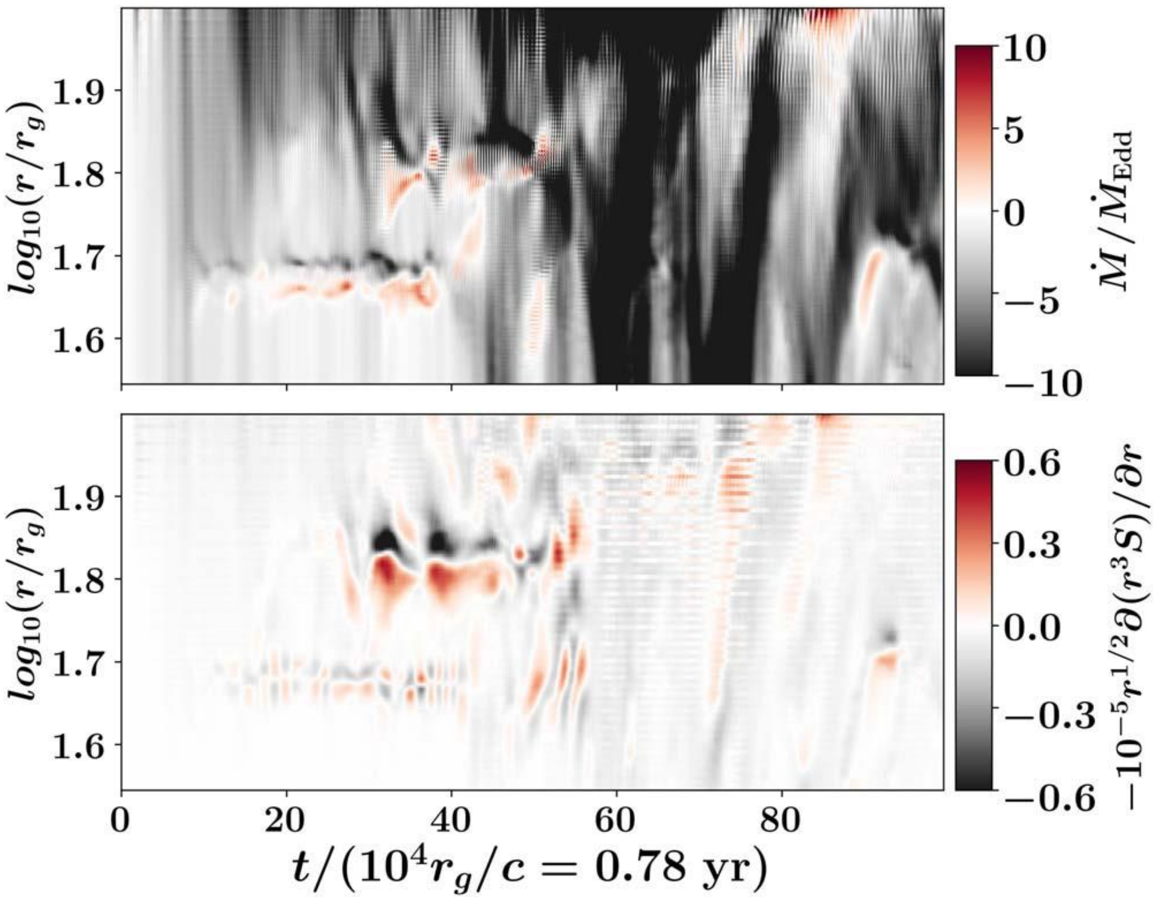
Iron Opacity Effects in AGN Disks



-Jiang & Blaes (2020)

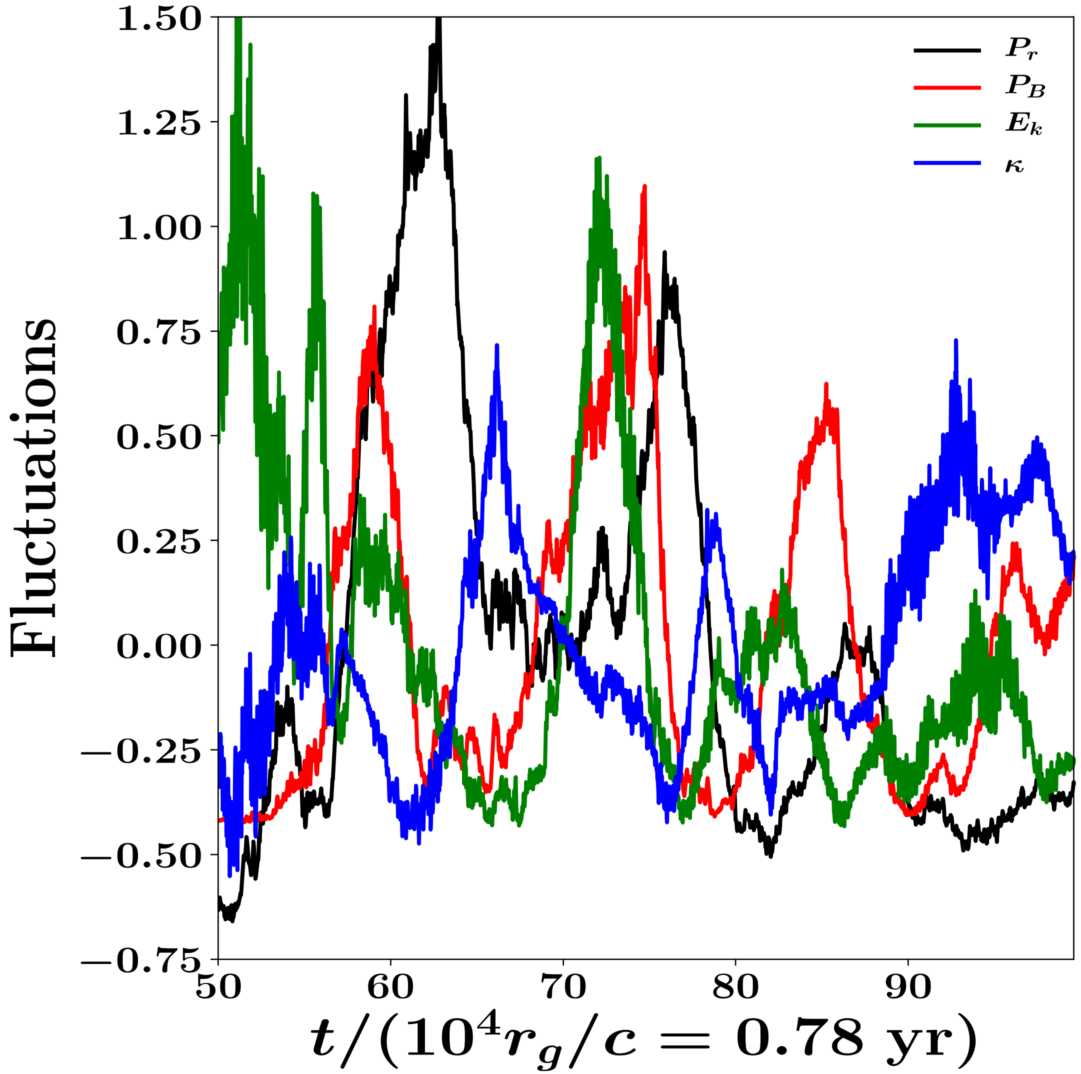
Radial Clumping of Material in Disk is Caused by Radial Gradients in Enhanced Stress Associated with Convective Cycles





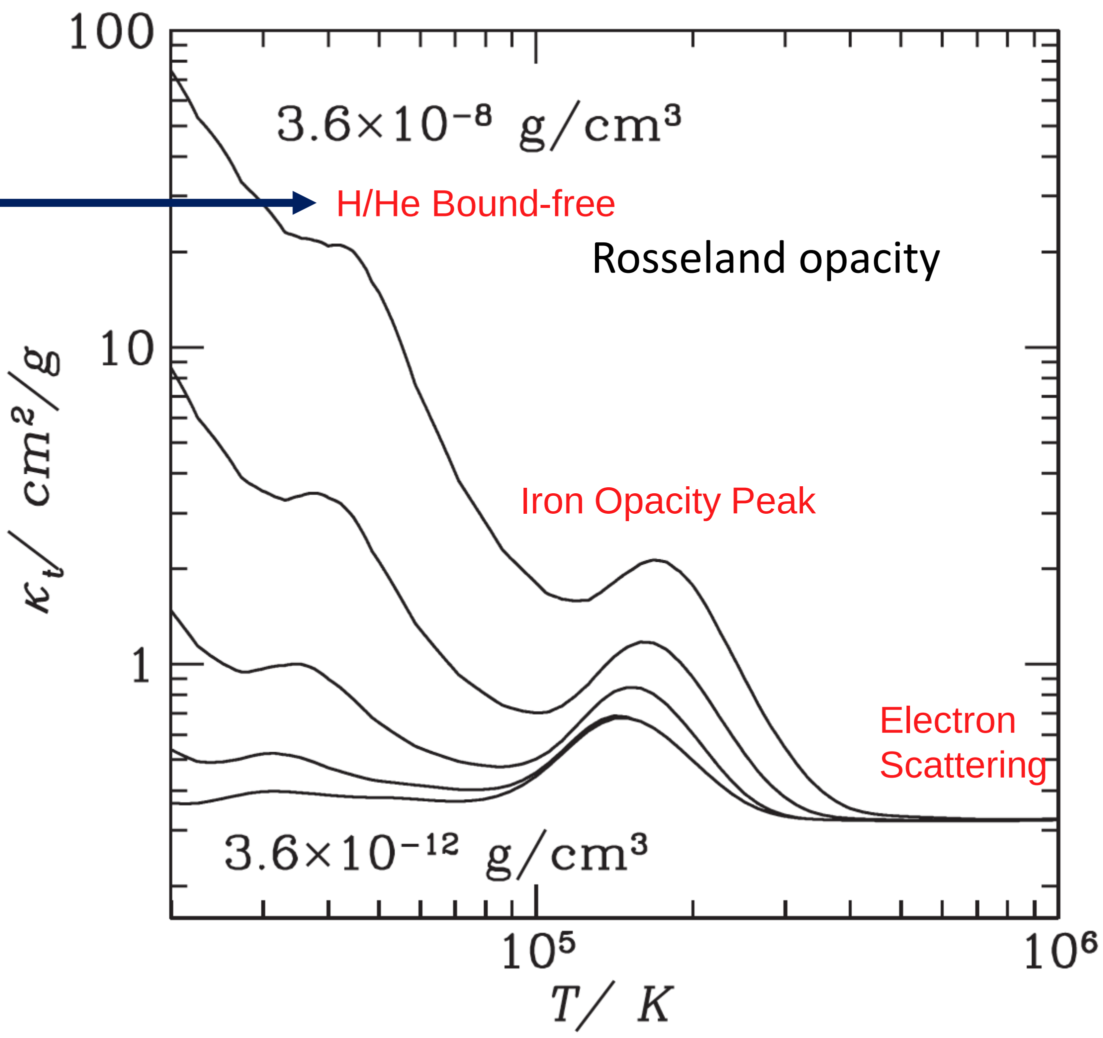
-Jiang & Blaes (2020)

Time history of fluctuations at r=50r_g



-These convection/MRI cycles are also seen in shearing box radiation MHD simulations of hydrogen (Hirose et al. 2014, Scepi et al. 2018) and helium (Coleman et al. 2018) CVs, and FU Orionis disks (Hirose 2015). MRI and convective turbulence interact in highly nontrivial ways (see also Held & Latter 2021).

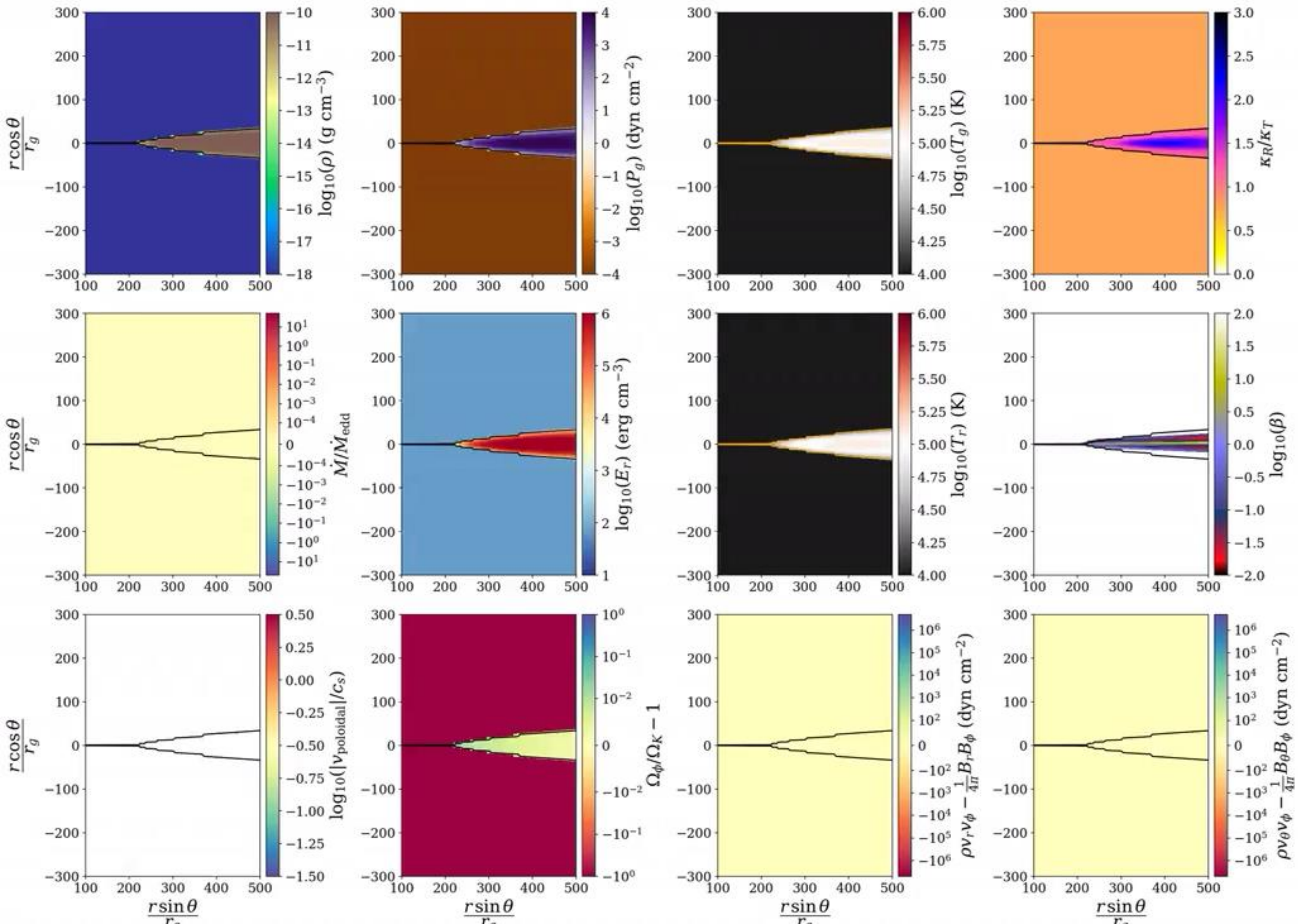
Can we tickle the dragon?

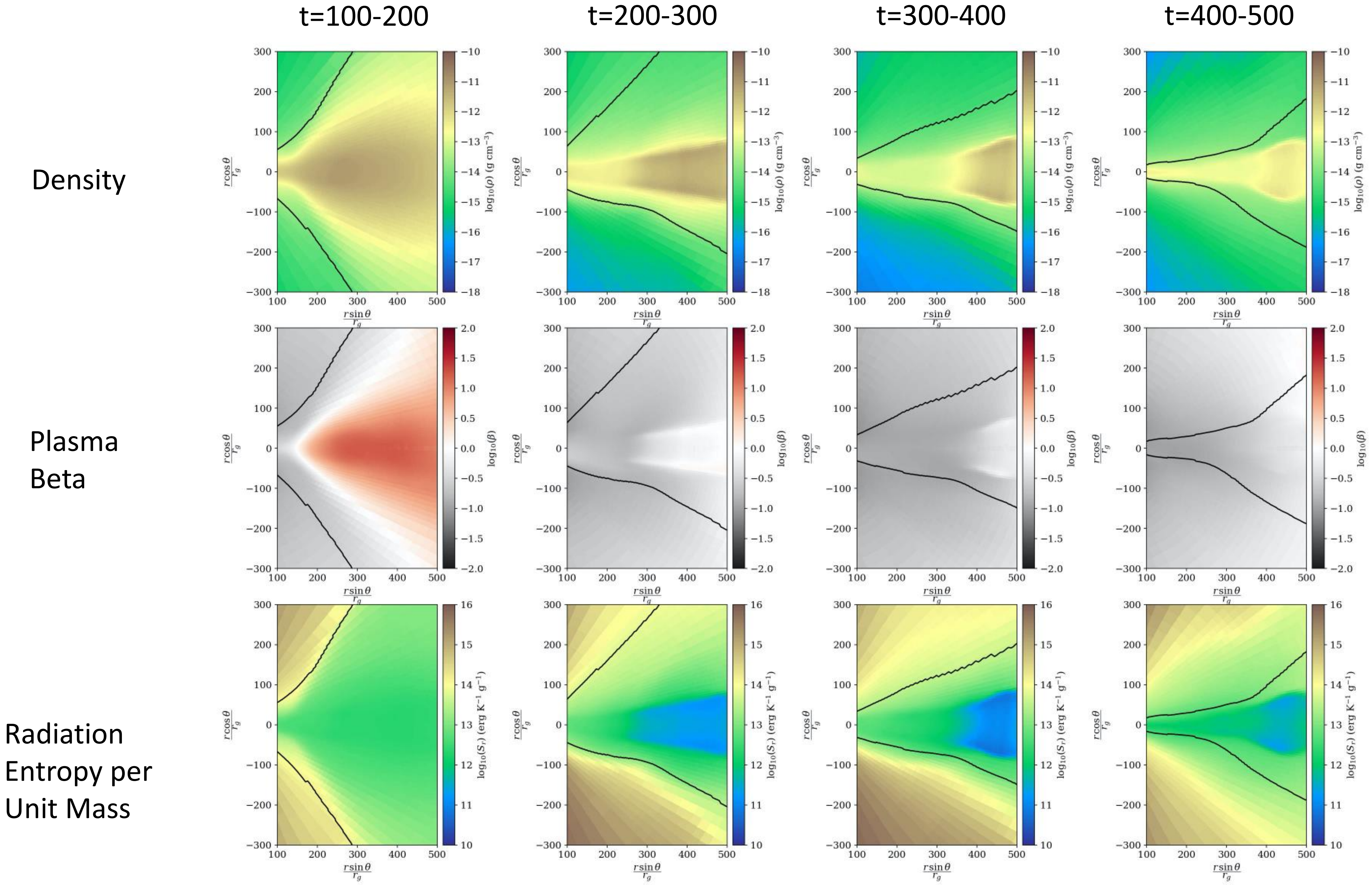


-Jiang et al. (2015)

AGNWedge16/History
t=0.00$t_{\rm sim}$

t_{sim}=4x10^{6}s



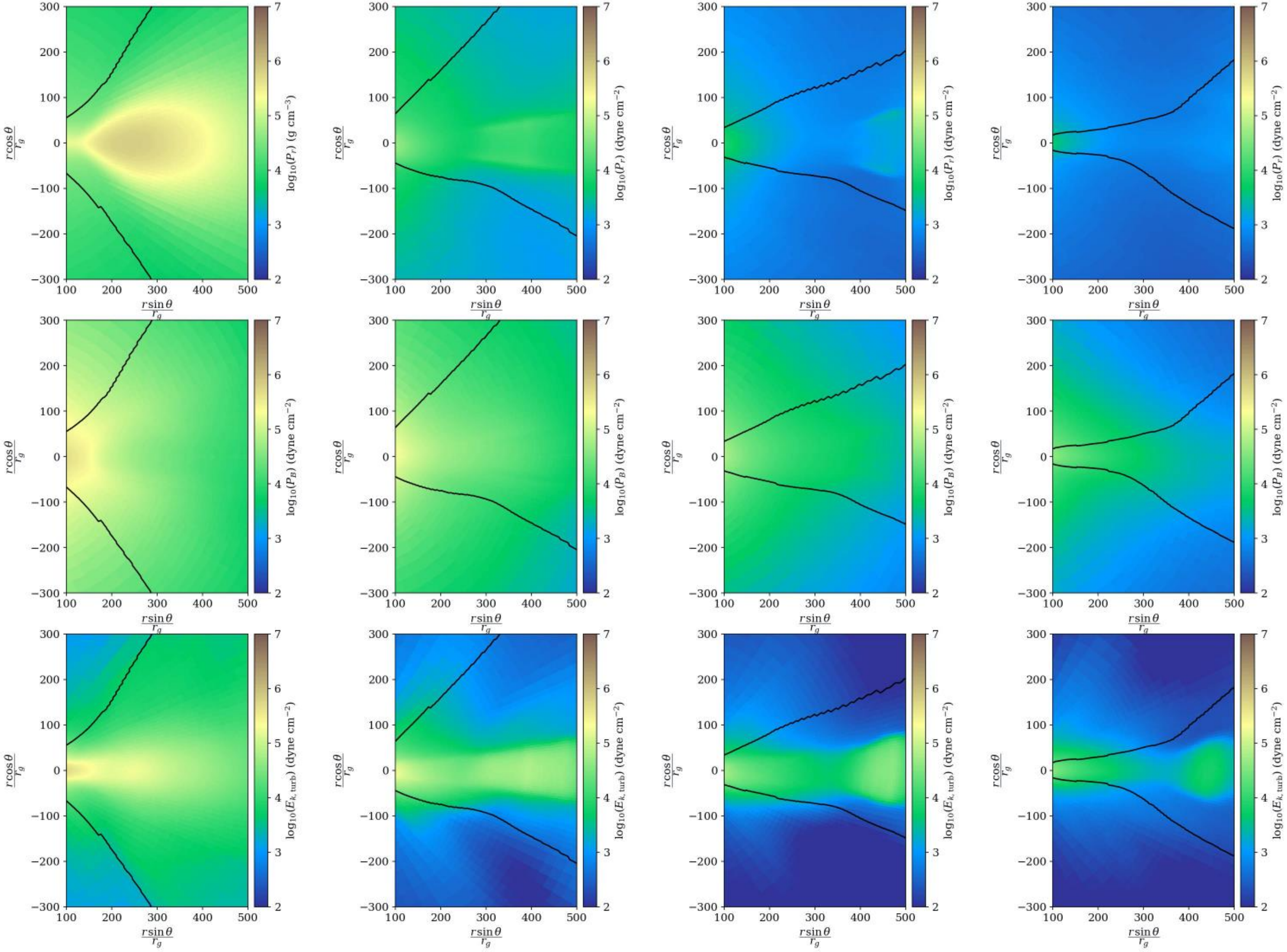

t=100-200
t=200-300
t=300-400
t=400-500
Density
Plasma
Beta
Radiation
Entropy per
Unit Mass
$\frac{r\cos\theta}{r_g}$
$\frac{r\sin\theta}{r_g}$
$\log_{10}(\rho)$ (g cm^{-3})
$\log_{10}(\beta)$
$\log_{10}(S_r)$ (erg K^{-1} g^{-1})

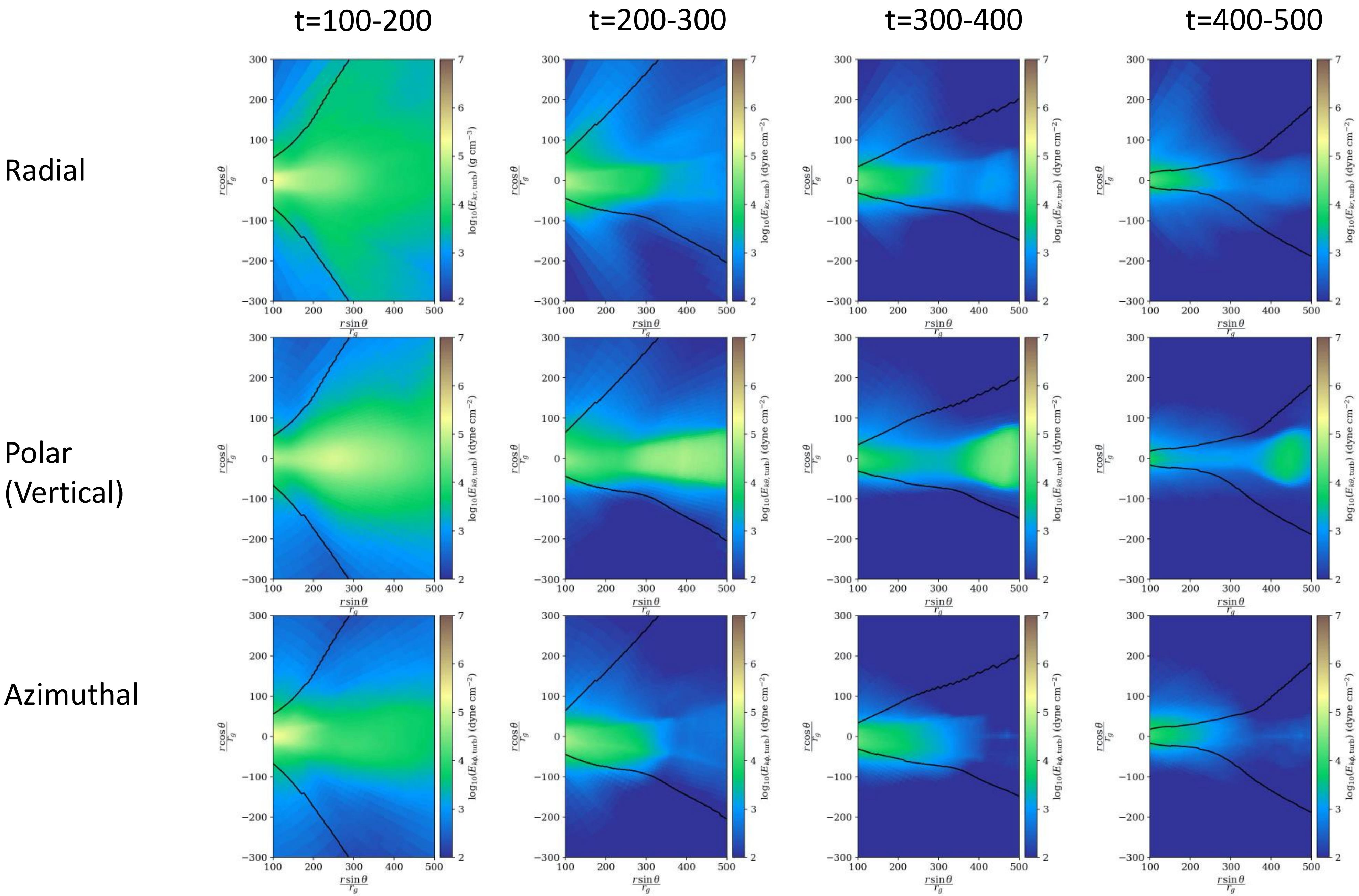
t=100-200 t=200-300 t=300-400 t=400-500

Radiation pressure

Magnetic pressure

Turbulent kinetic energy density

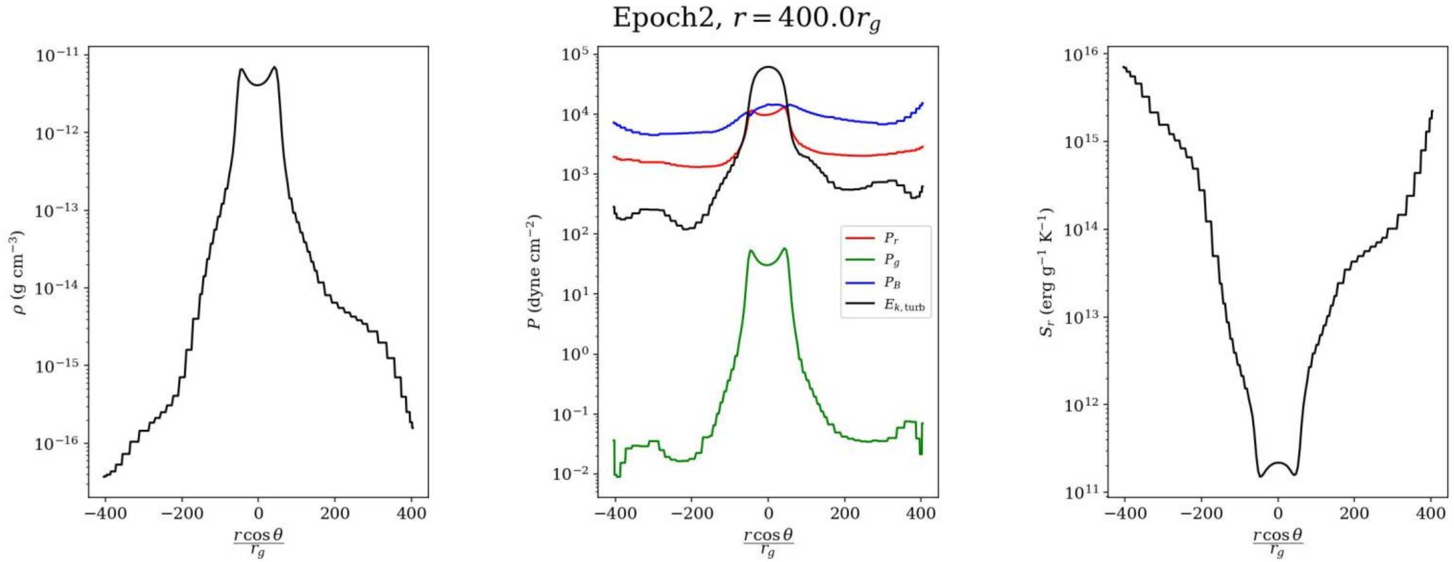




Contributions to turbulent kinetic energy density: polar dominates in regions of iron opacity-driven convection.

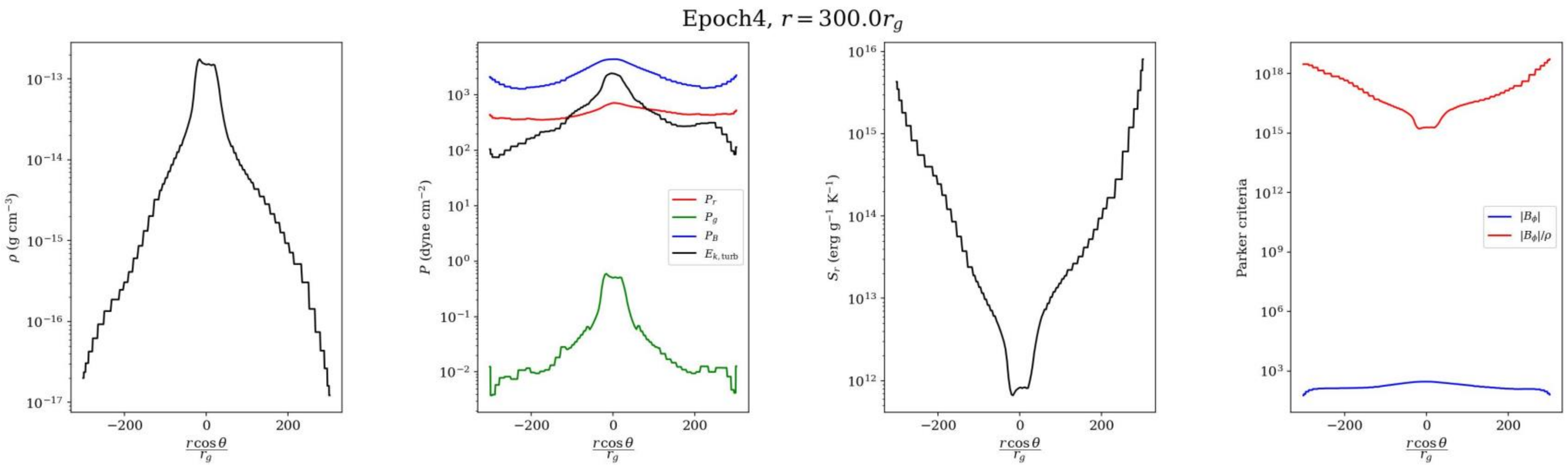
“Vertical” Profiles at Fixed Radius

Convective



Turbulent kinetic energy completely dominates in midplane (supersonic and super-Alfvénic).

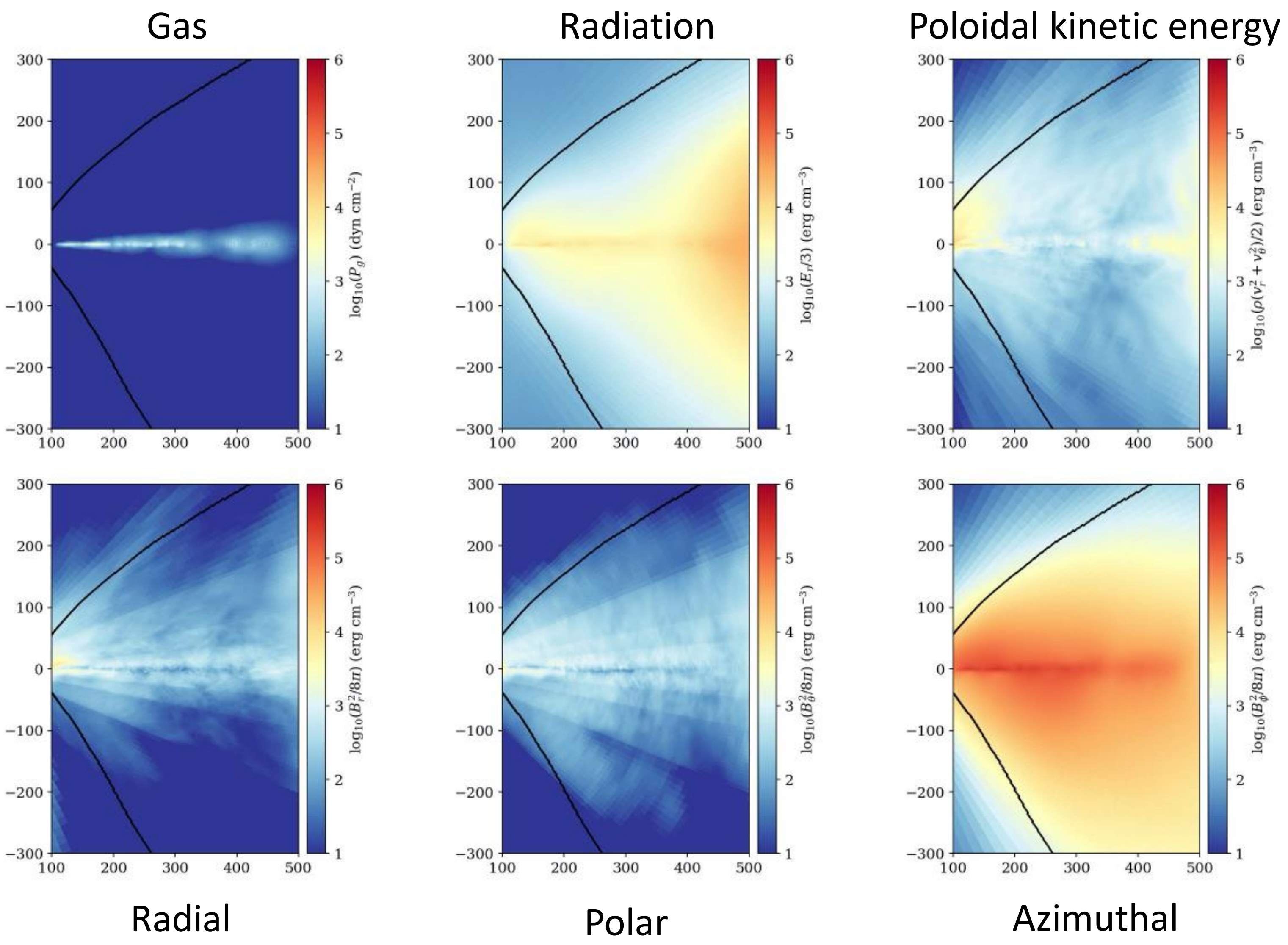
Magnetically dominated



Turbulent kinetic energy is nearly in equipartition with magnetic energy, similar to assumption of Pariev et al. (2003).

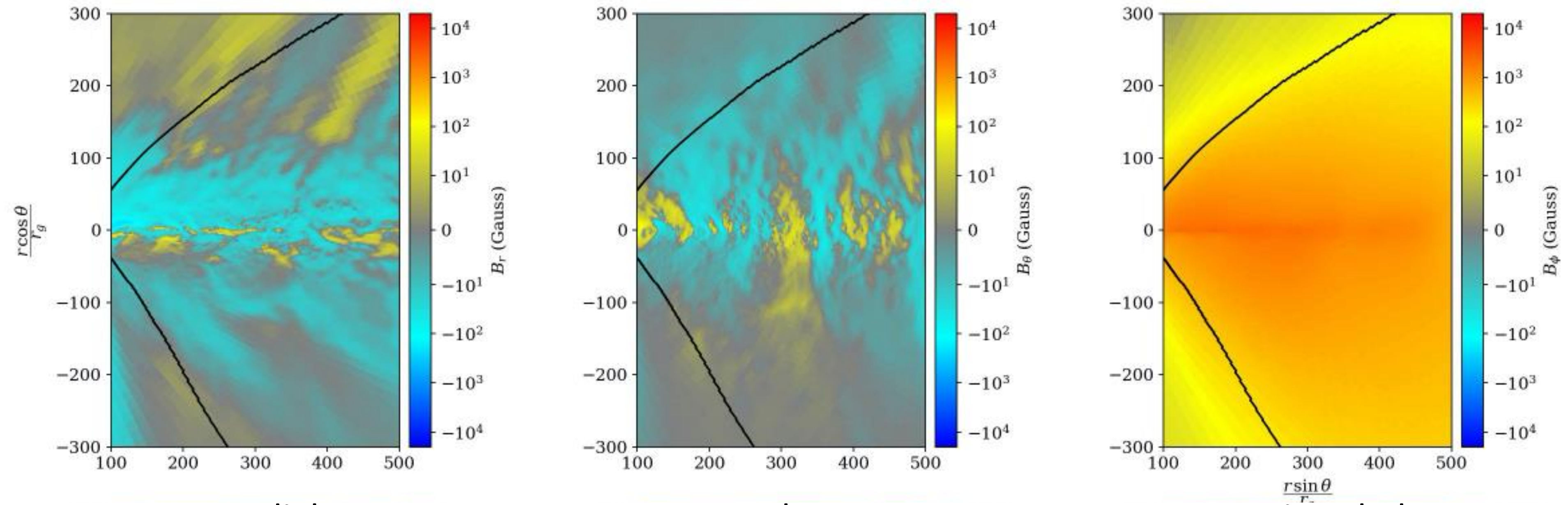
A (Very) Magnetically-Dominated Flow

Time-averaged pressures

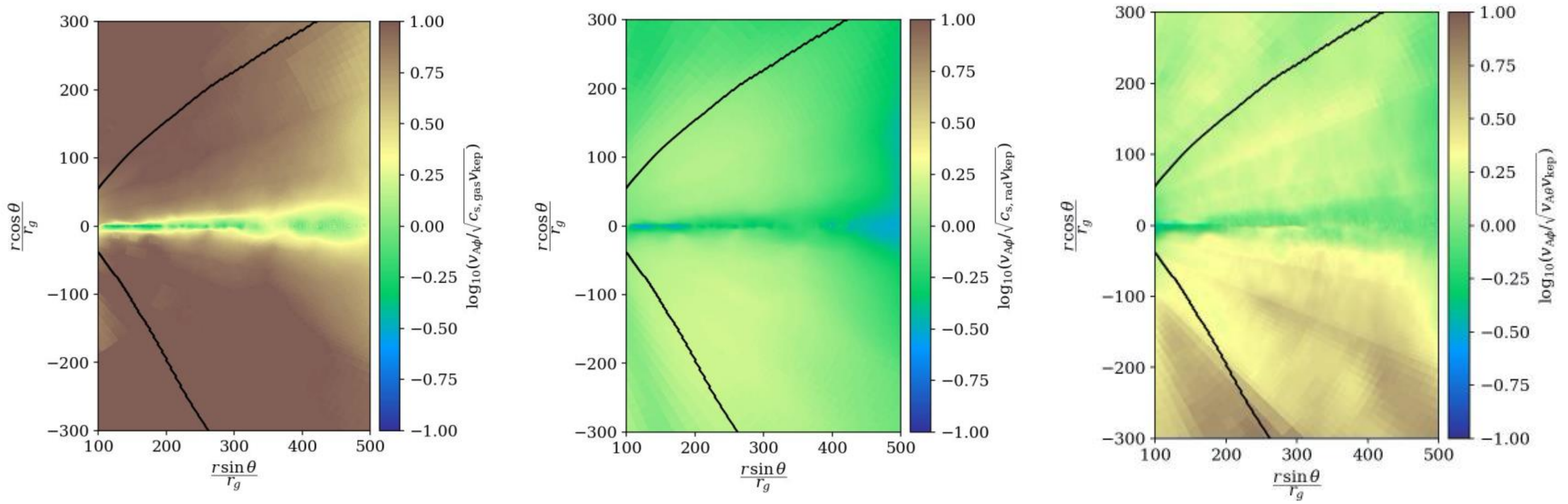


Magnetic pressures

Time-Averaged Field Components



Radial Polar Azimuthal



Comparison with various models of B-field saturation (Begelman & Pringle 2007; Begelman & Armitage 2023).

Summary

- AGN are characterized by similar opacities to those of massive star envelopes, resulting in (inefficient) turbulent convection.

- This intermittent convection cyclically enhances MRI stresses, driving transient clumping of surface density and large amplitude variability on the local thermal time scale. (This might explain the characteristic time scale observed in DRW modeling.)

- (Supersonic!) turbulent kinetic energy is a substantial and sometimes dominant source of pressure support.

- Magnetically elevated/dominated, SANE disks also exhibit substantial (Alfvénic) turbulent kinetic energy, and appear to be long-lived.

- Have not (yet) triggered continuum opacity-driven outflows, and also still need to model the magnetically dominated flows.

These are not Shakura-Sunyaev disks.