AGN Accretion Disk Physics and Variability

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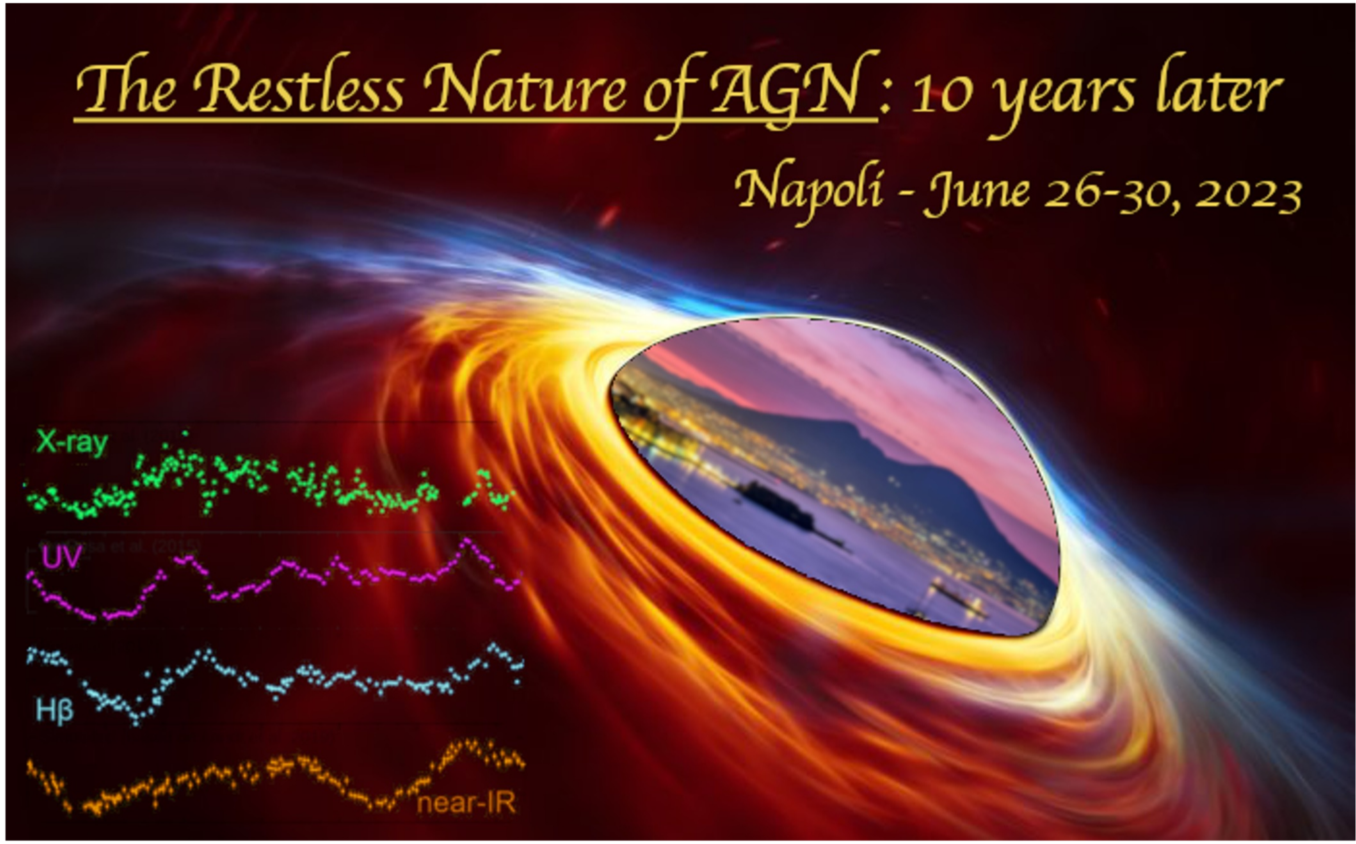


Luminous AGN are Probably Powered by Optically Thick Accretion In Which Accretion Power is Thermalized into Radiation at Some Level

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

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

cf. standard (Newtonian) disk theory:

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

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

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

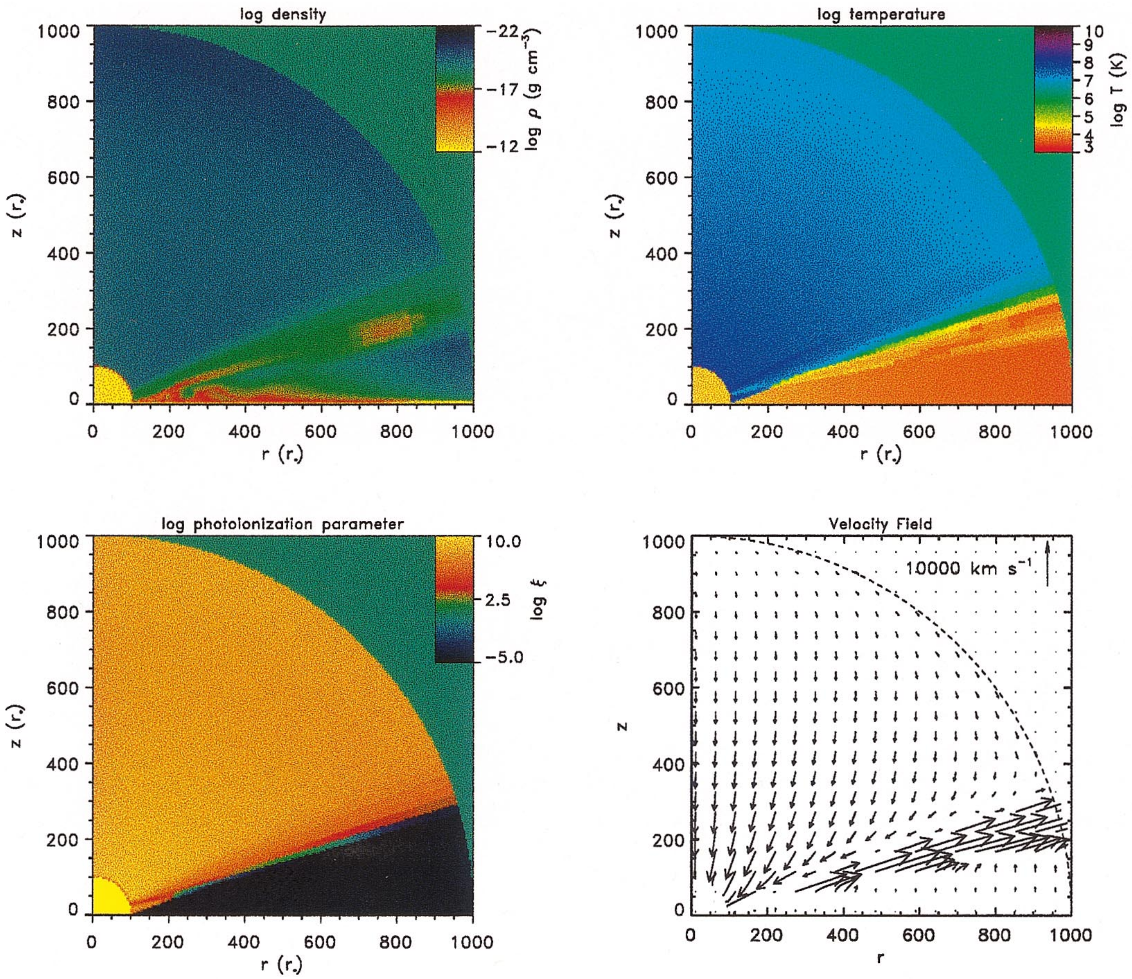
- UV spectra have a quasi-universal shape with a break to a power-law at $1000\,\text{Å}$ (near the Lyman limit), nothing like what accretion disk theory predicts.

- Microlensing and reverberation mapping place the optical emission radius to be about a factor 3 larger than standard accretion disk theory predicts.

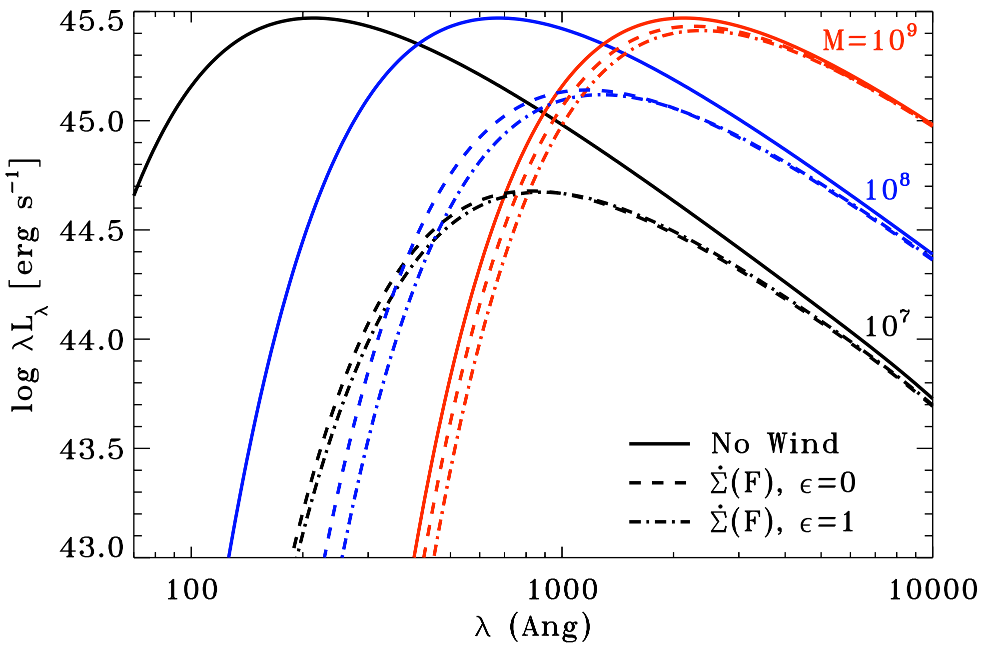
- Observed variability occurs on very rapid time scales compared to standard disk theory, the most extreme manifestation being so-called Changing Look Quasars.

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

Disk Winds Are Almost Certainly the Major Modifier of Far UV SED



-Proga, Stone & Kallman (2000)



-Laor & Davis (2014)

Winds can also alleviate the microlensing size problem (Li, Yuan & Dai 2019).

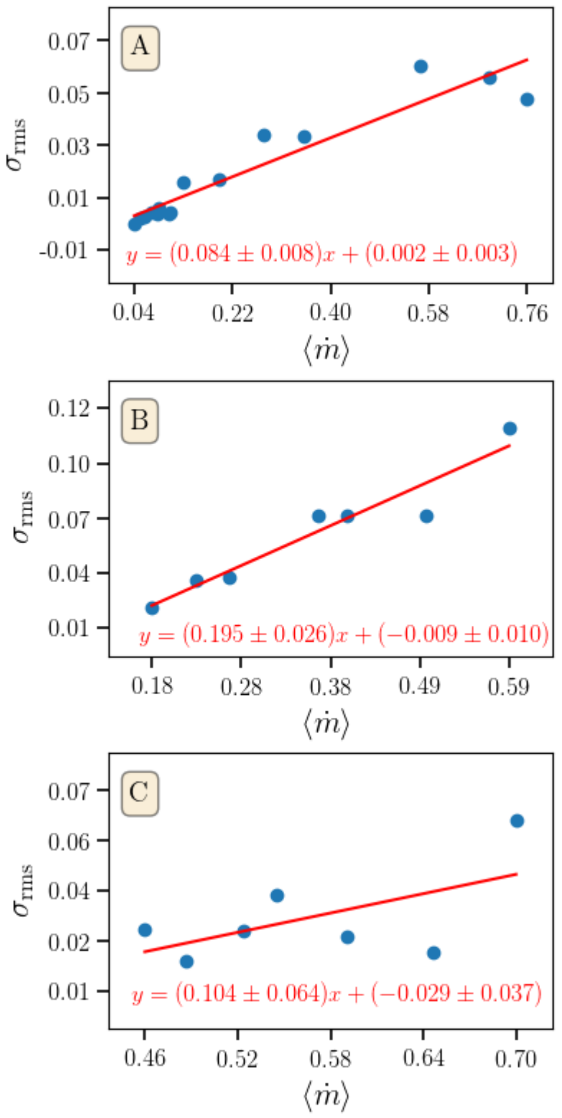
Secular Time Scales in the Standard Radiation Pressure Dominated Model

$$t_{\rm th} \equiv (\alpha\Omega)^{-1} = 20\ \text{days} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{50 r_{\rm g}}\right)^{3/2}$$

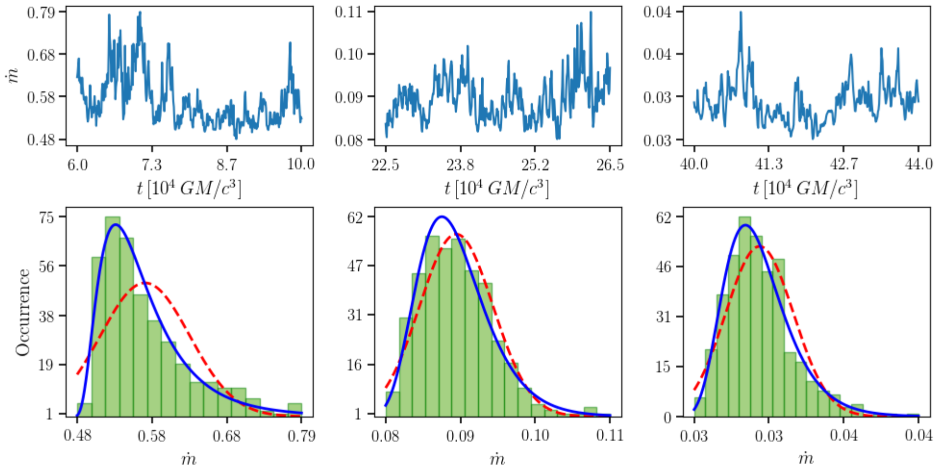
$$t_{\rm inflow} \equiv (\alpha\Omega)^{-1} \left(\frac{r}{H}\right)^{2} = 22000\ \text{days} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{50 r_{\rm g}}\right)^{7/2} \left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-2} \left(\frac{\dot{M}}{\eta \dot{M}_{\rm Edd}}\right)^{-2}$$

Vertical hydrostatic equilibrium + radiation diffusion $\Rightarrow$ $H = \dfrac{3\dot{M}}{8\pi c}\kappa = \dfrac{3}{2} r_{\rm g} \left(\dfrac{\kappa}{\kappa_{\rm T}}\right) \left(\dfrac{\dot{M}}{\eta \dot{M}_{\rm Edd}}\right)$

Global Non-Radiative GRMHD Simulations Do Exhibit Nonlinear RMS-Accretion Rate and Lognormal Distributions



RMS - <Accretion Rate>



Accretion Rate Distributions Fit by Gaussian (red) and Lognormal (Blue)

-Bollimpalli et al. (2020)

(see also Samuel Turner's poster for some insight into *why* this is happening.)

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!

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

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

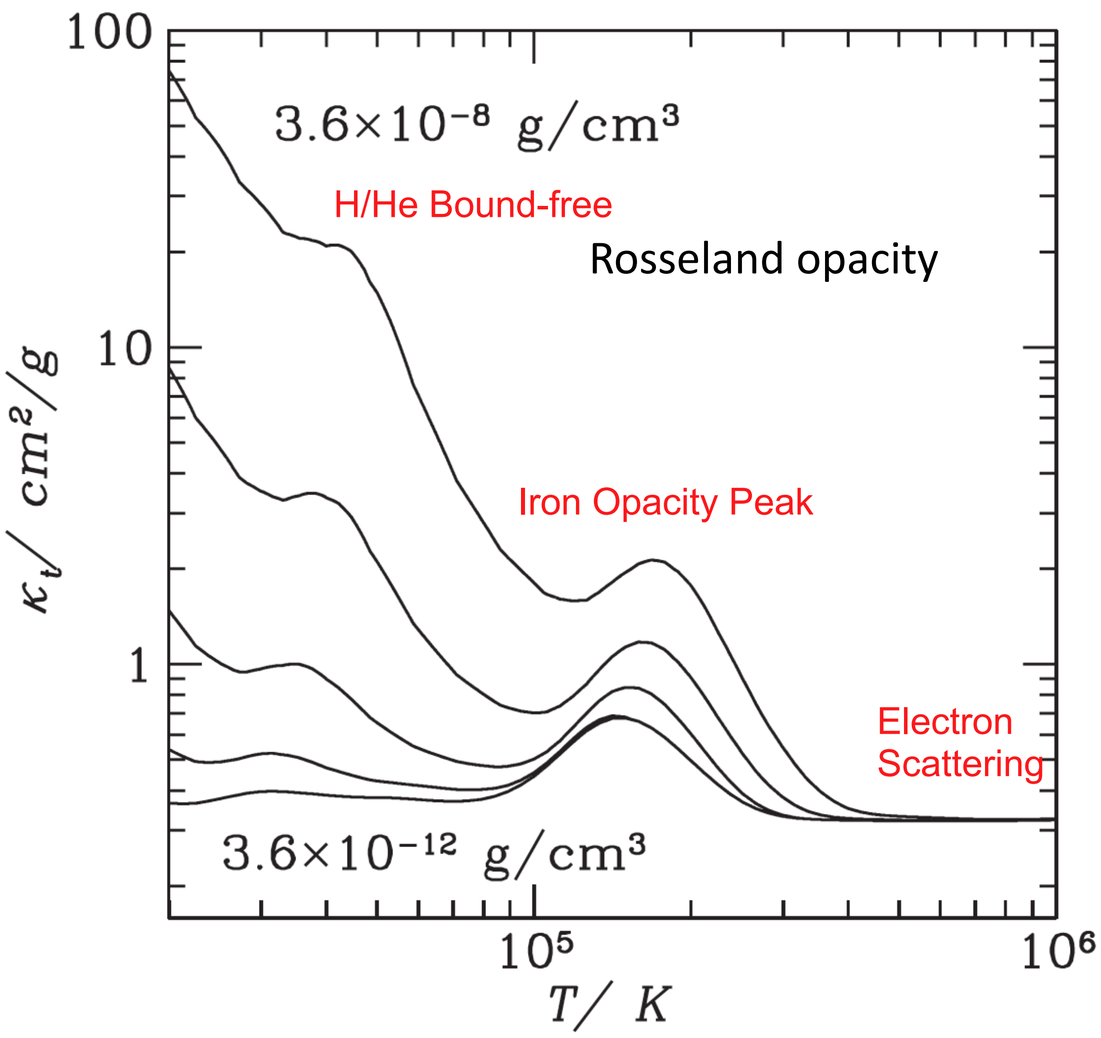
$$L(r) = 4\pi r\Delta r\frac{acT^4}{3\kappa\rho H}$$

IF diffusive transport

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

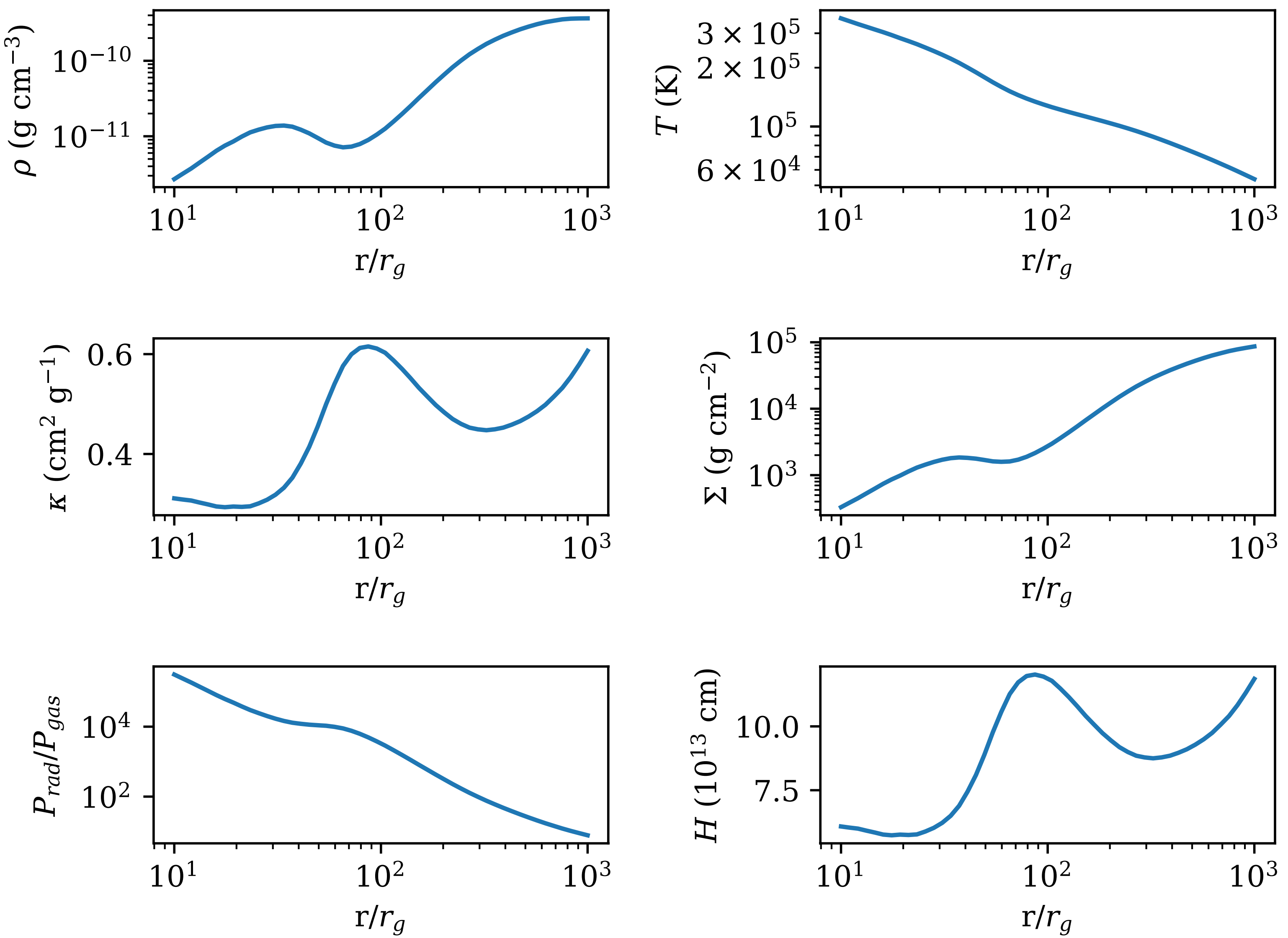
$$\frac{P_\text{rad}}{P_\text{gas}} = 1 \times 10^7\alpha^{1/4}\left(\frac{M}{10^8 M_\odot}\right)^{1/4} f_\text{rad}^{3/4}\left(\frac{r}{r_\text{g}}\right)^{-9/8}\left(\frac{H}{r}\right)^{3/2}\left(\frac{\kappa}{\kappa_\text{T}}\right)^{3/4}\left(\frac{\dot{M}}{\eta\dot{M}_\text{Edd}}\right)^{1/2}$$

The Iron Opacity Peak in FUV Temperature Plasmas



-Jiang et al. (2015)

Radial Structure in the Standard Shakura-Sunyaev Disk Model with Realistic Rosseland Opacities



$M = 10^8\ \mathrm{M}_\odot,\ \dot{M}/(\eta \dot{M}_{\mathrm{Edd}}) = 3$, and $\alpha = 0.1$

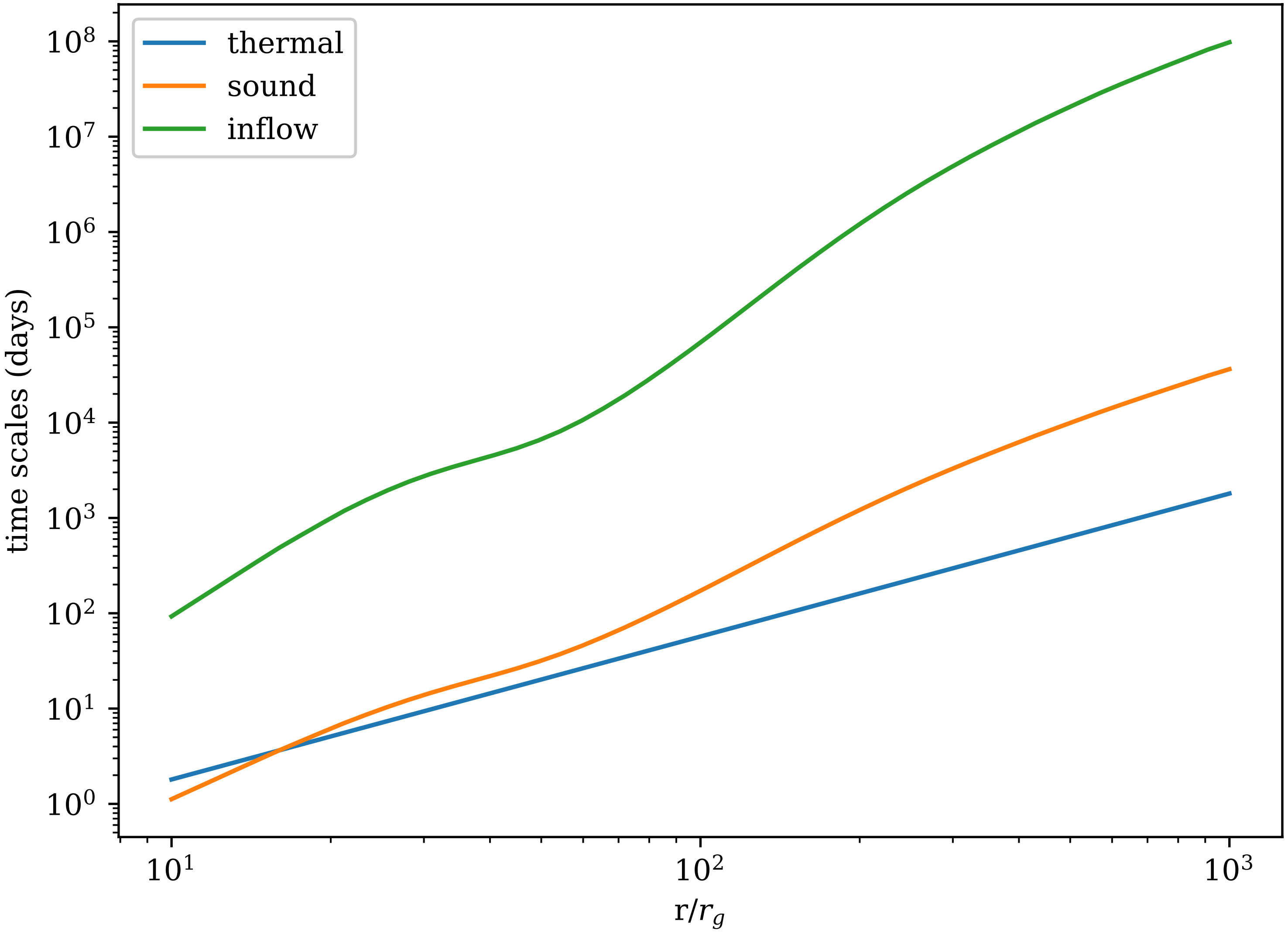
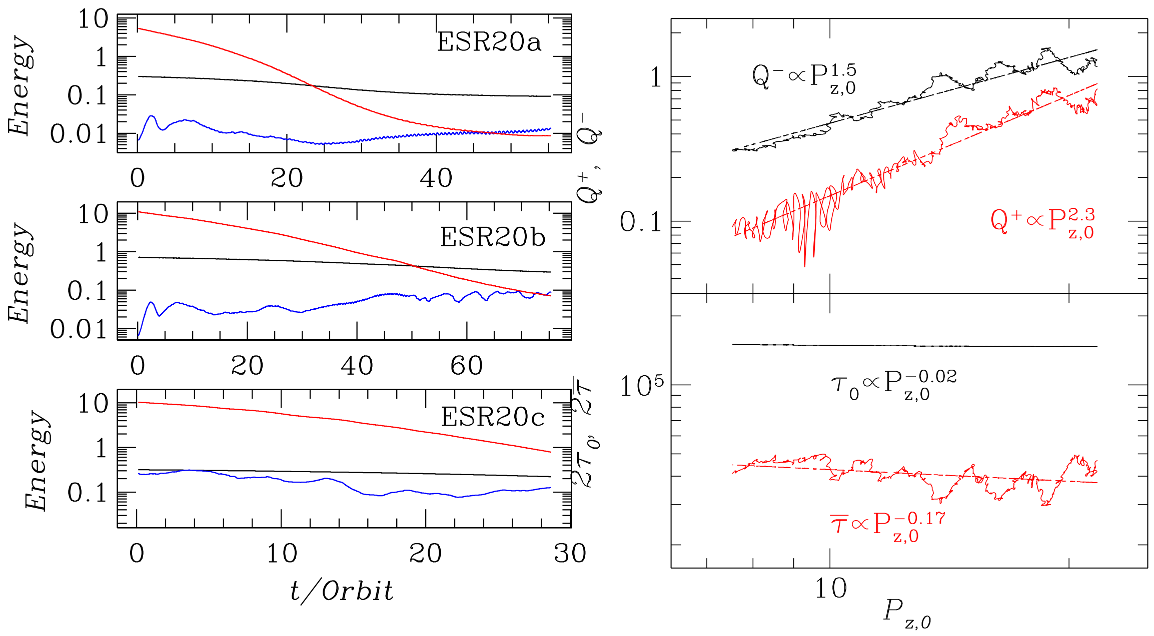


Figure 5: Characteristic time scales in the standard alpha disk model with realistic opacities, assuming $M = 10^8$ $M_\odot$, $\dot{M}/(\eta \dot{M}_{\rm Edd}) = 1$, and $\alpha = 0.1$.

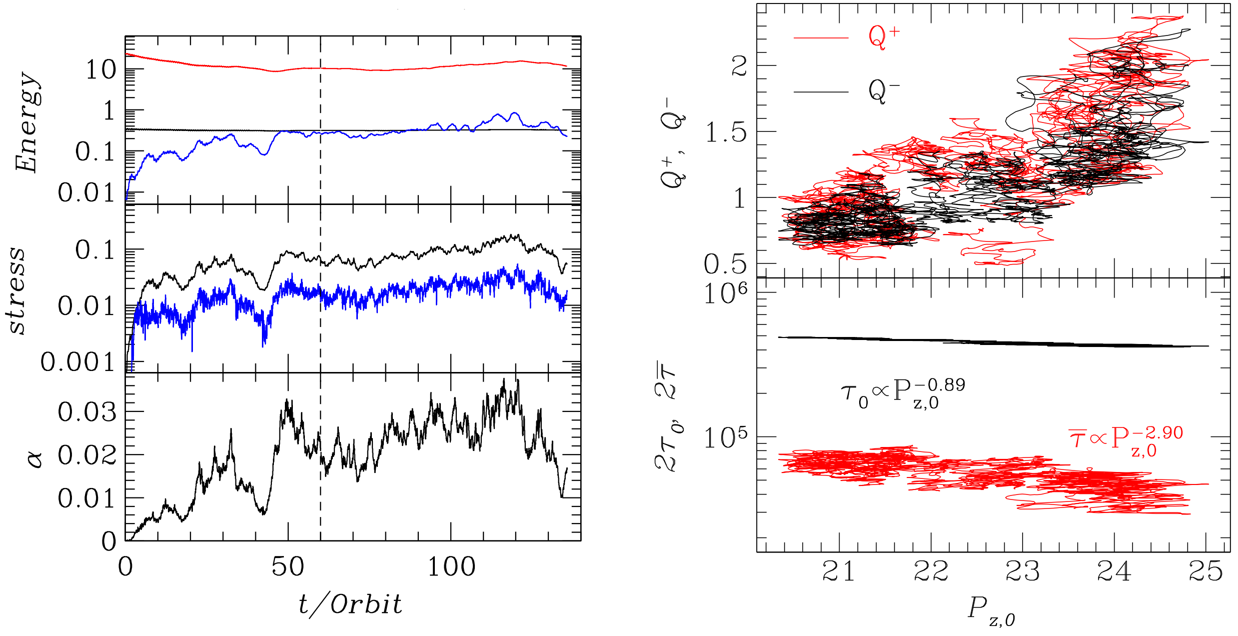
Iron Opacity Bump May Stabilize the Radiation-Pressure Dominated Thermal Instability

Electron scattering + free-free:



Disk collapses!

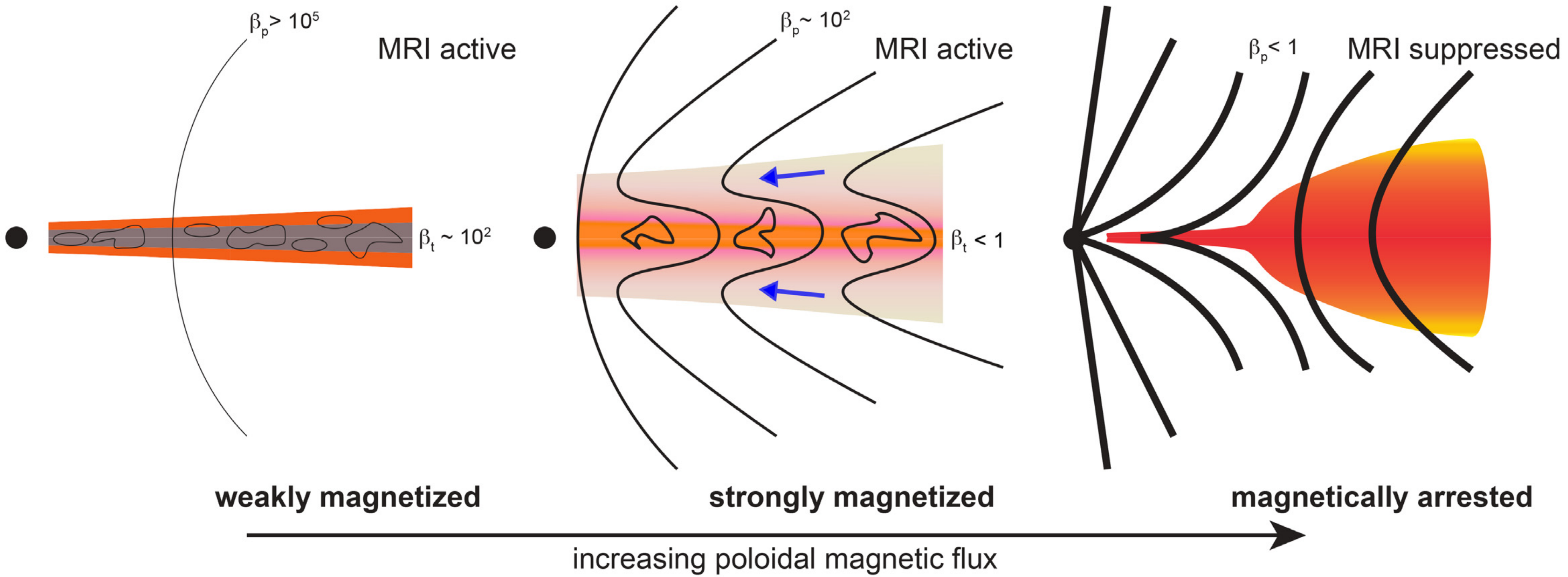
OPAL Opacities:



Disk achieves a long-lived thermal equilibrium, stabilized by inverse relationship between optical depth and pressure, as well as enhanced cooling from advection of radiation by buoyant magnetic fields.

Vertically stratified radiation MHD simulations by Jiang, Davis & Stone (2016).

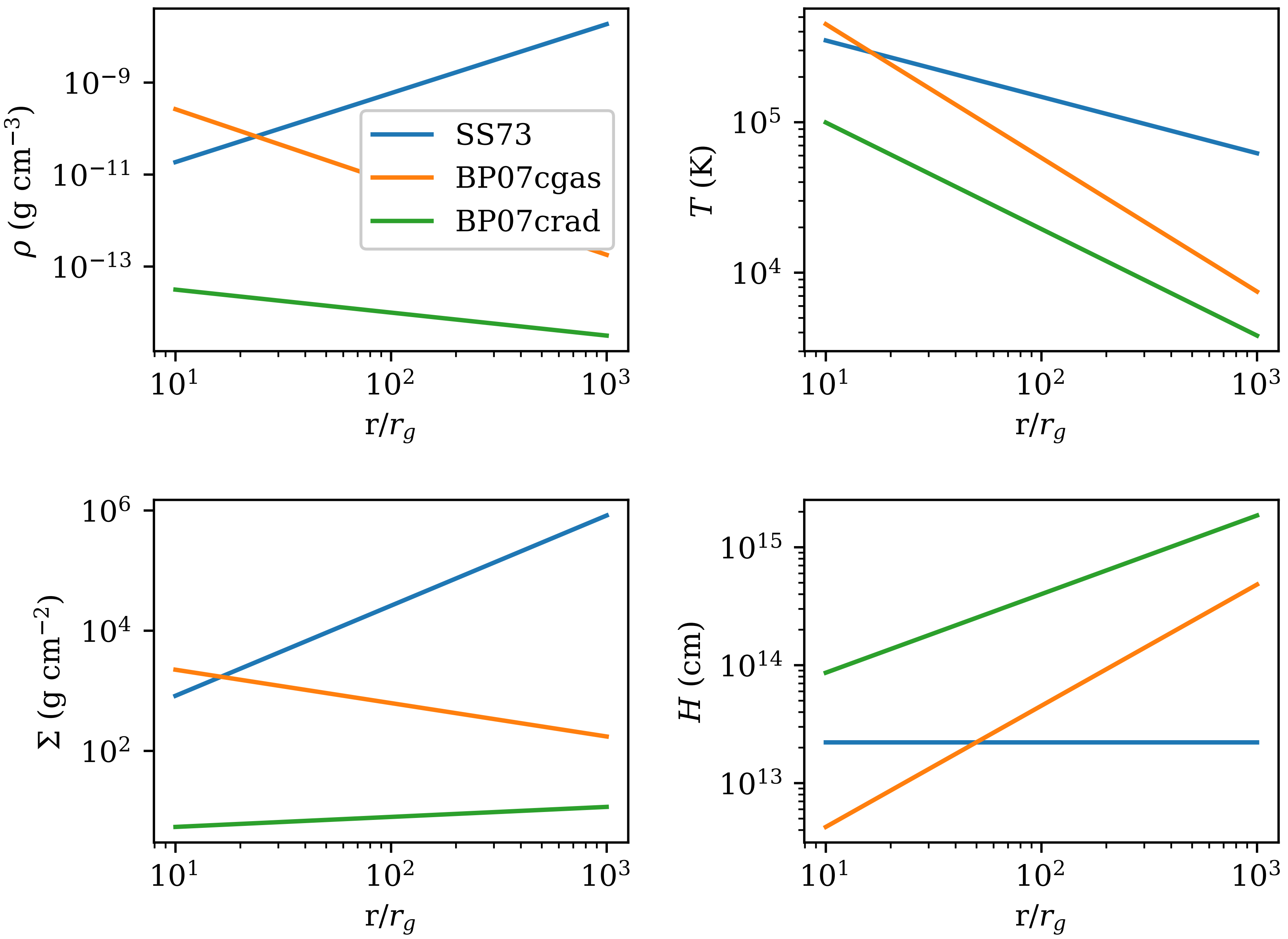
The Effects of Poloidal Magnetic Fields



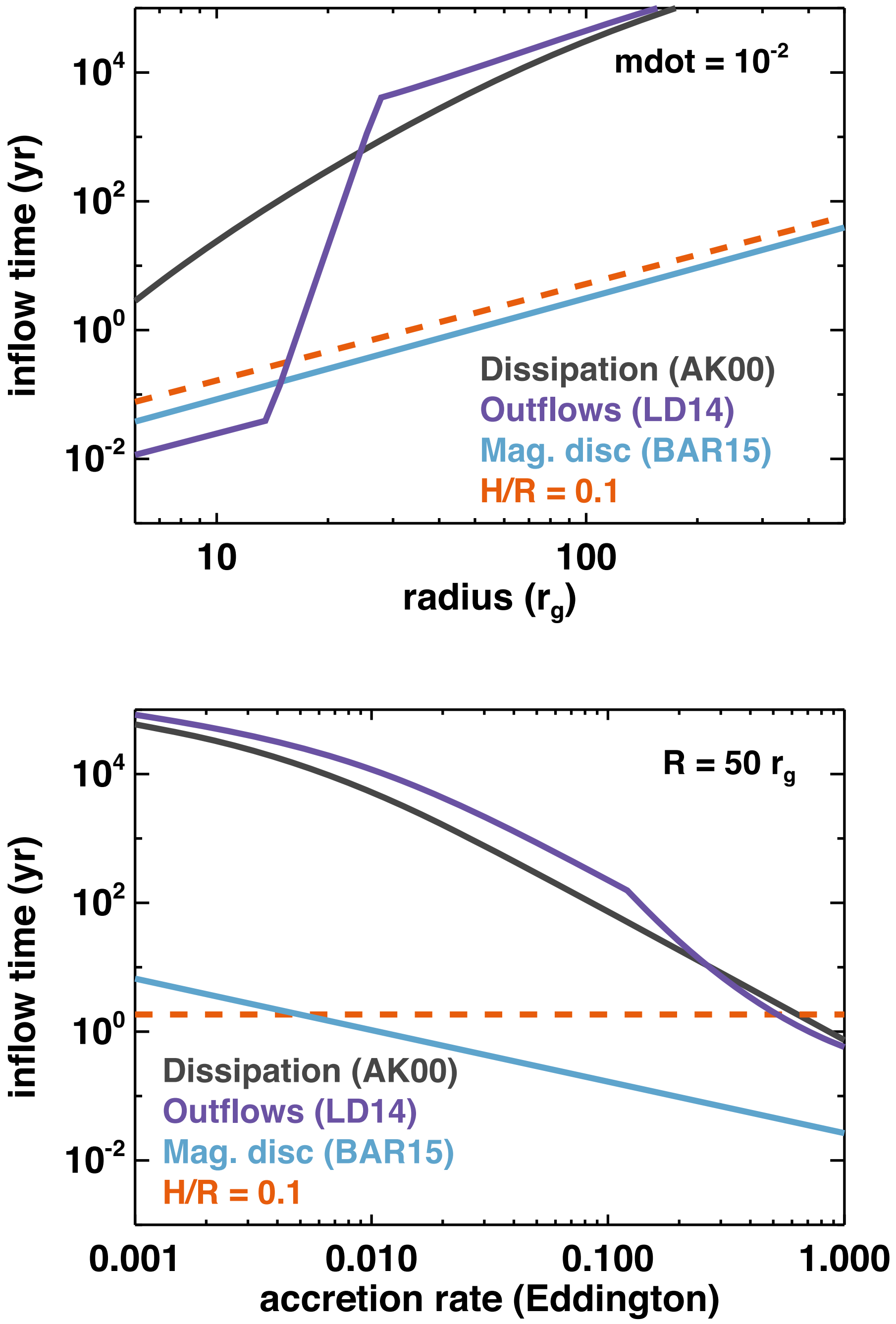
-Mishra et al. (2020)

Magnetic pressure support also stabilizes the radiation pressure dominated instability (Begelman & Pringle 2007, Sadowski 2016).

Magnetically Elevated Disk Structure



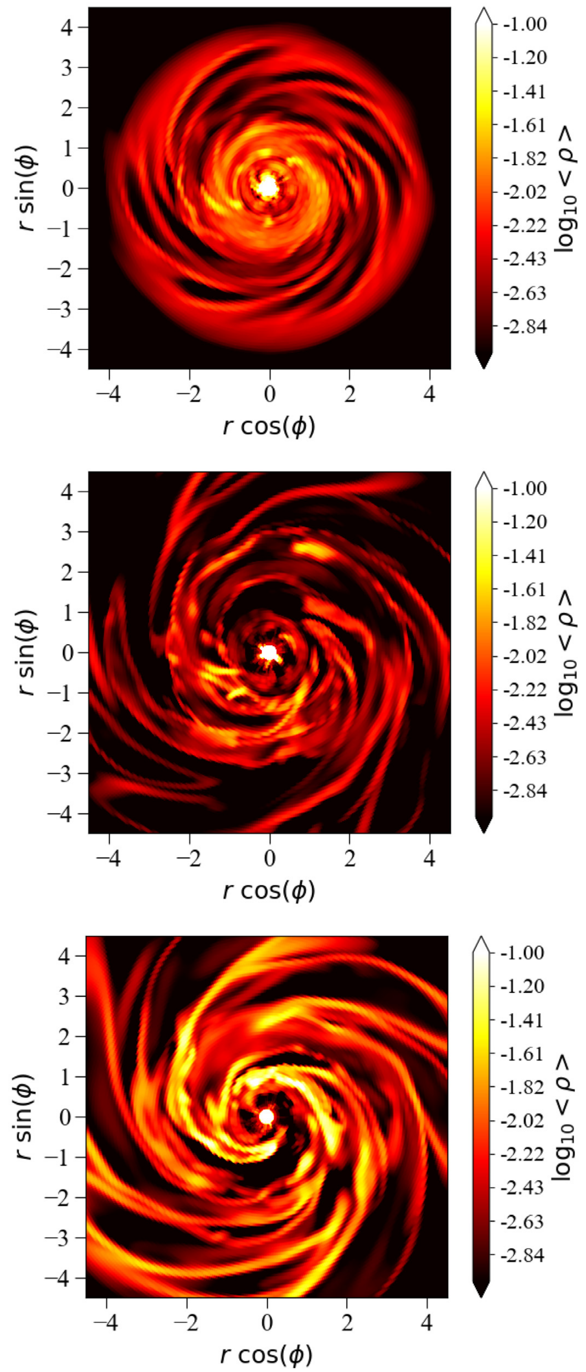
-Figures based on equations of Begelman & Pringle (2007)



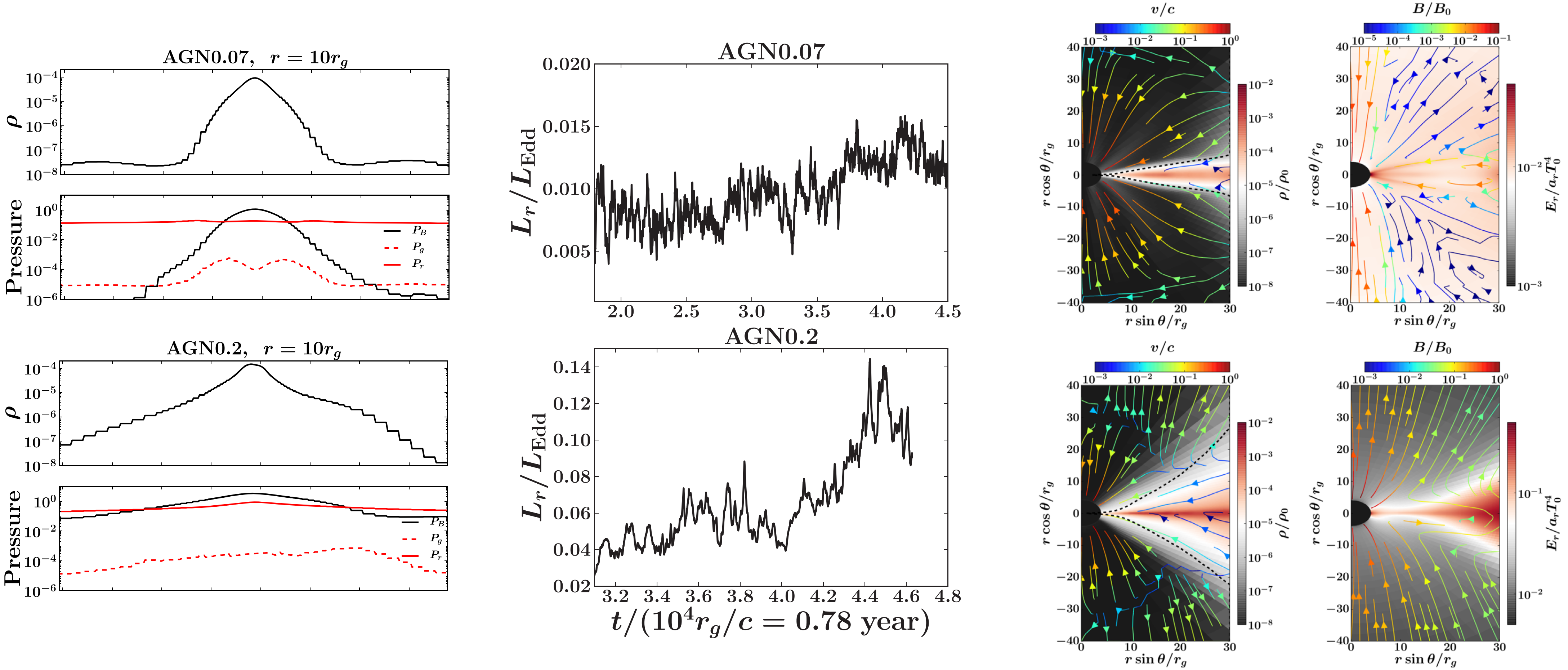
-Dexter & Begelman (2019)

Strong nonaxisymmetric density fluctuations can occur in magnetically elevated disks. (Non-radiative, locally isothermal MHD simulations by Mishra et al. 2020.)

Cf. inhomogeneous disks of Dexter & Agol (2011)?

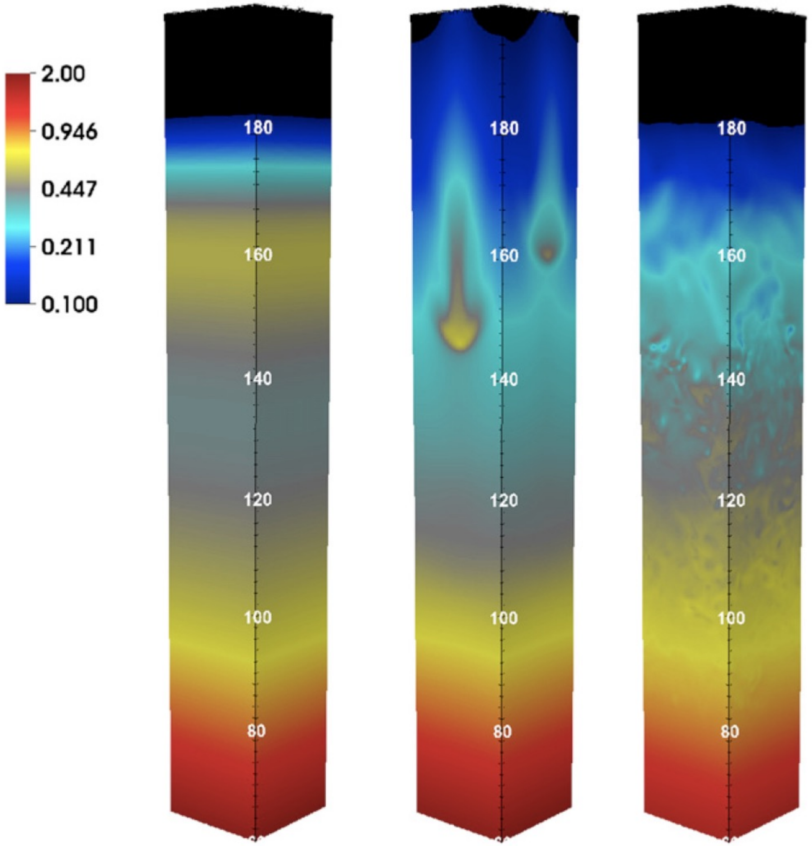


Global Radiation MHD Simulations of Magnetically Elevated Disks in AGN

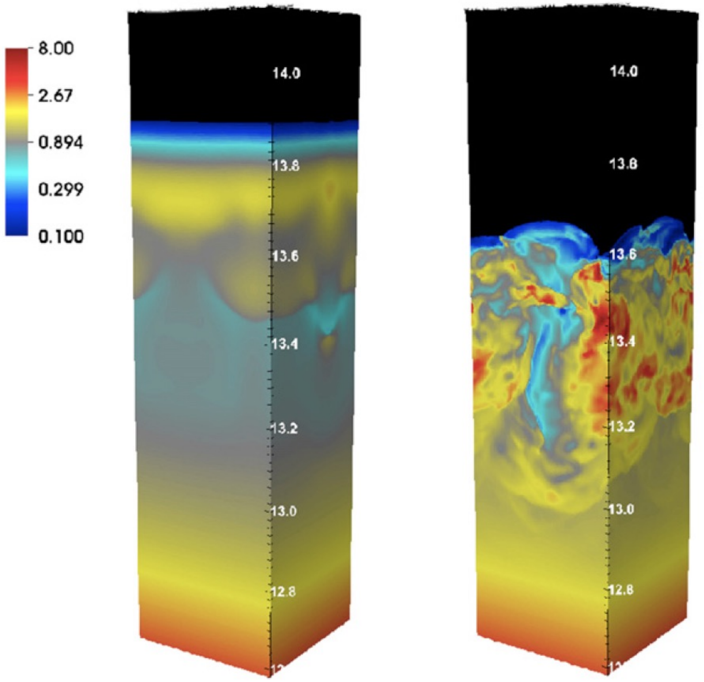


-Jiang et al. (2019)

Iron Opacity Effects in Massive Stars



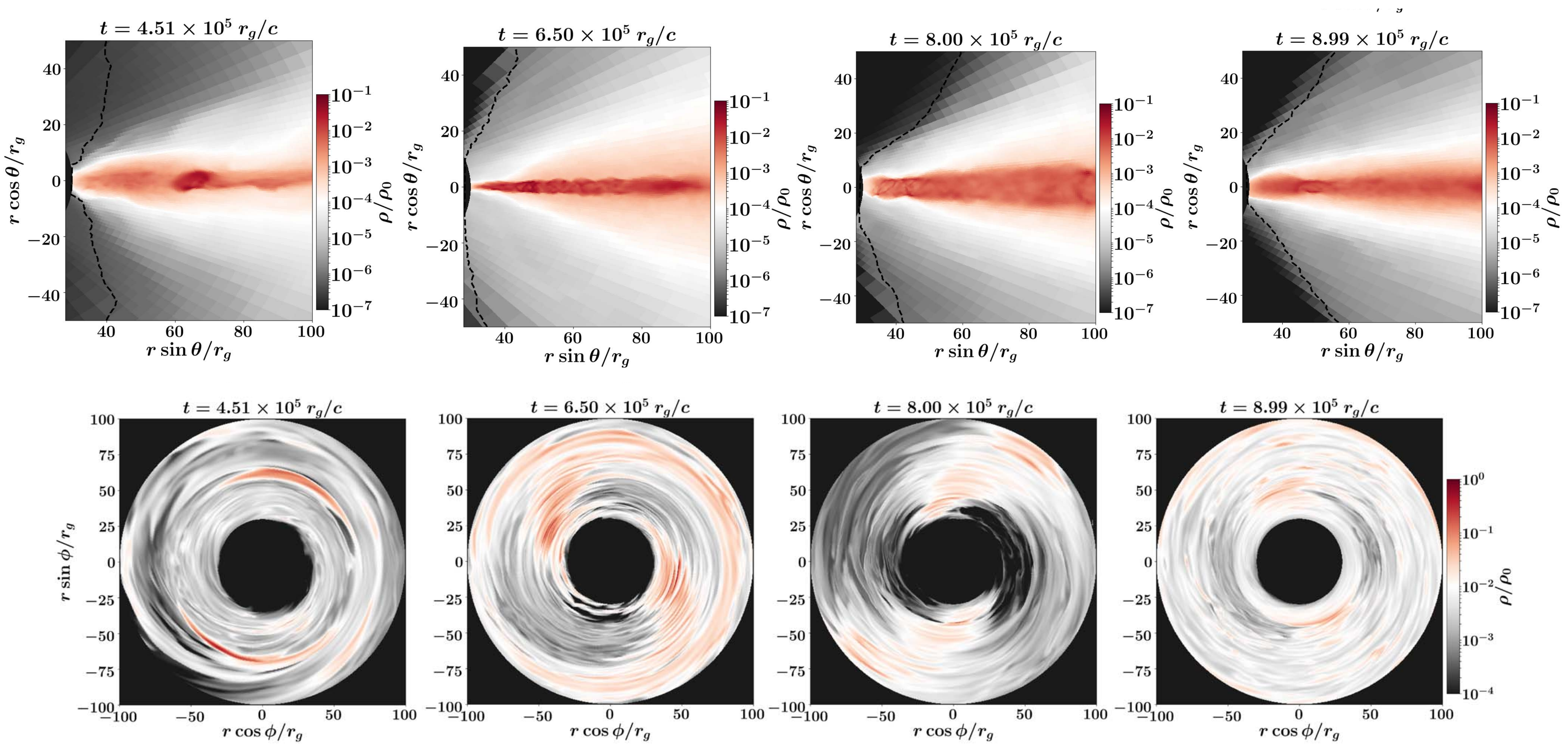
Slow photon diffusion:
density inversion wiped out
and convection is efficient.



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

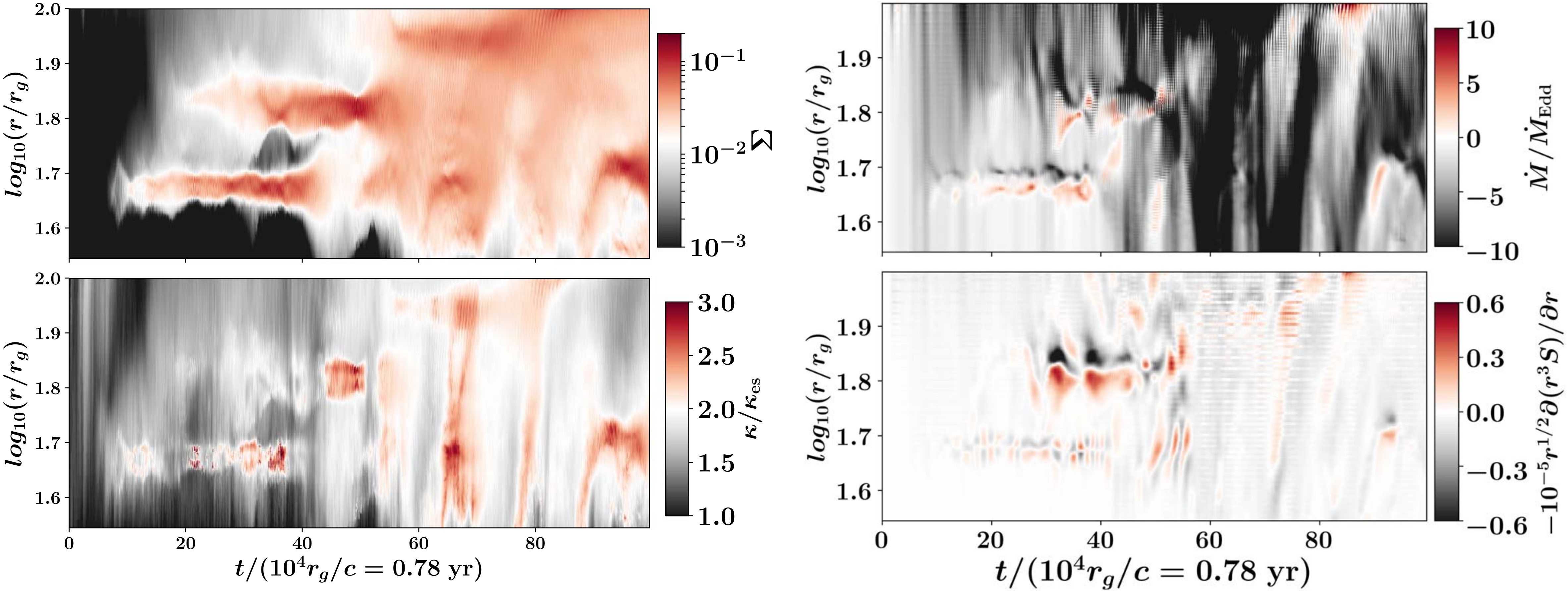
-Jiang et al. (2015)

Iron Opacity Effects in AGN Disks

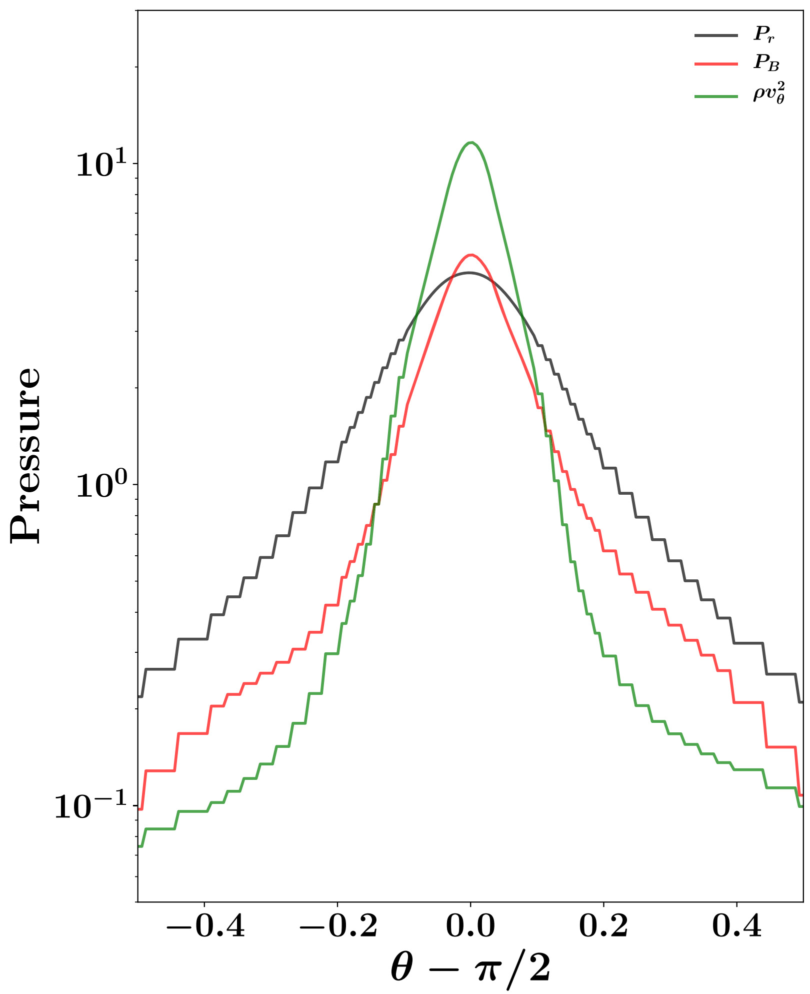


-Jiang & Blaes (2020)

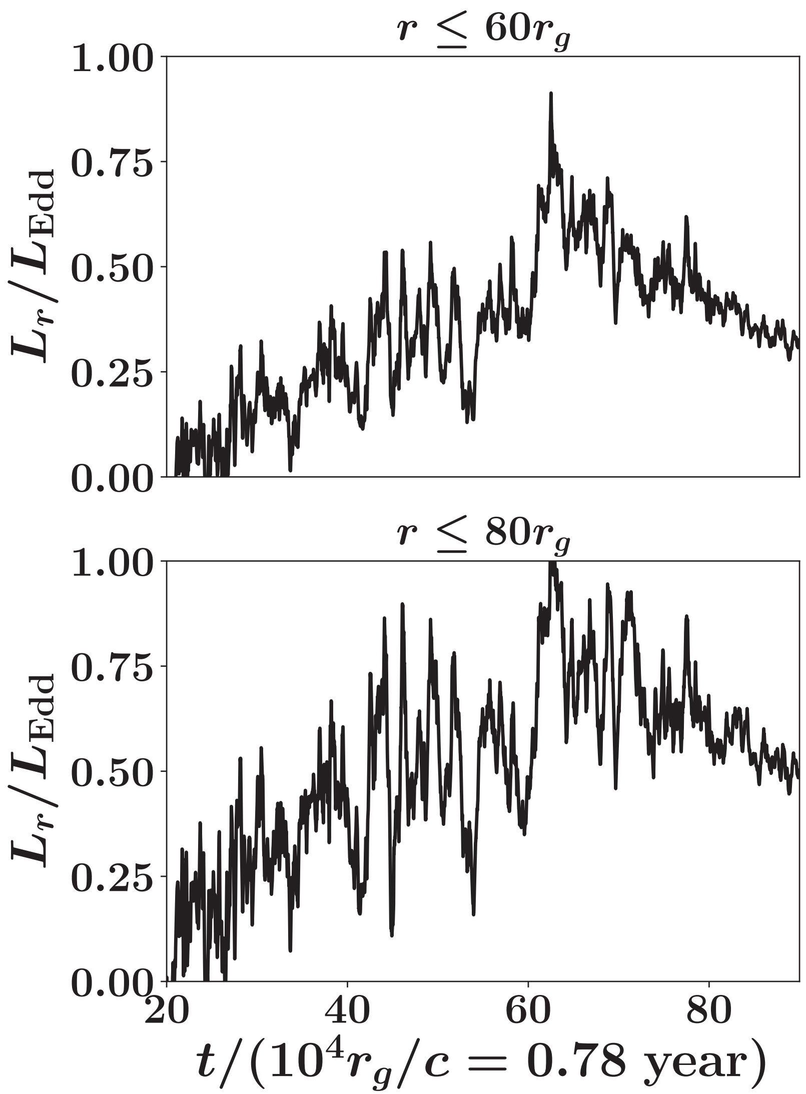
Radial Clumping of Material in Disk is Caused by Radial Gradients in Enhanced Stress Associated with Convective Cycles



-Jiang & Blaes (2020)



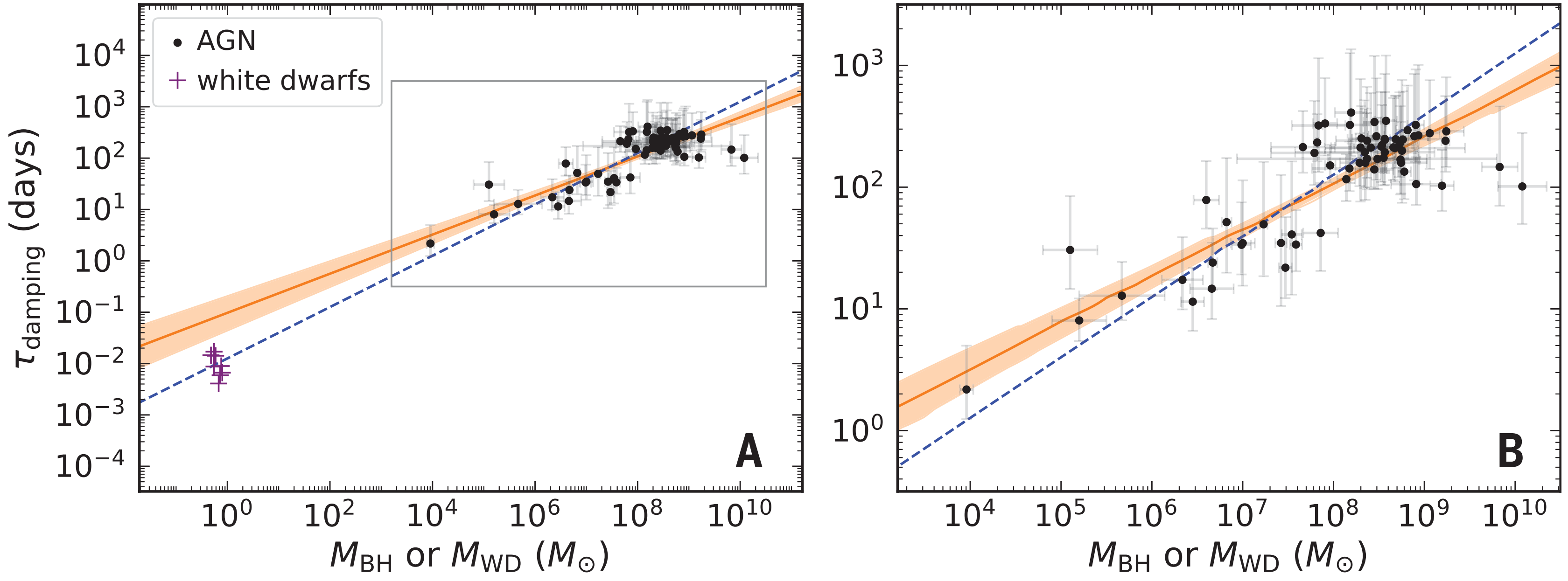
Hydrostatic support is provided by turbulent kinetic energy, not thermal or magnetic pressure.



Lots of variability!

A possible mechanism for driving AGN variability?

(Rest frame) damping time scale from DRW modeling of AGN light curves:



$$\tau_{\rm damping} = 107^{+11}_{-12}\ {\rm days} \left(\frac{M_{\rm BH}}{10^8\, M_\odot}\right)^{0.38^{+0.05}_{-0.04}}$$

-Burke et al. (2021)

Thermal Time in Iron Opacity Region (T=200,000 K) According to Standard Model

$$\frac{r}{r_{\rm g}} = \left(\frac{4c^8}{G^2M^2\alpha^2\kappa^2a^2T^8}\right)^{1/3} = 9.6\alpha^{-2/3}\left(\frac{\kappa}{\kappa_{\rm T}}\right)^{-2/3}\left(\frac{T}{2\times10^5{\rm K}}\right)^{-8/3}\left(\frac{M}{10^8M_\odot}\right)^{-2/3}$$

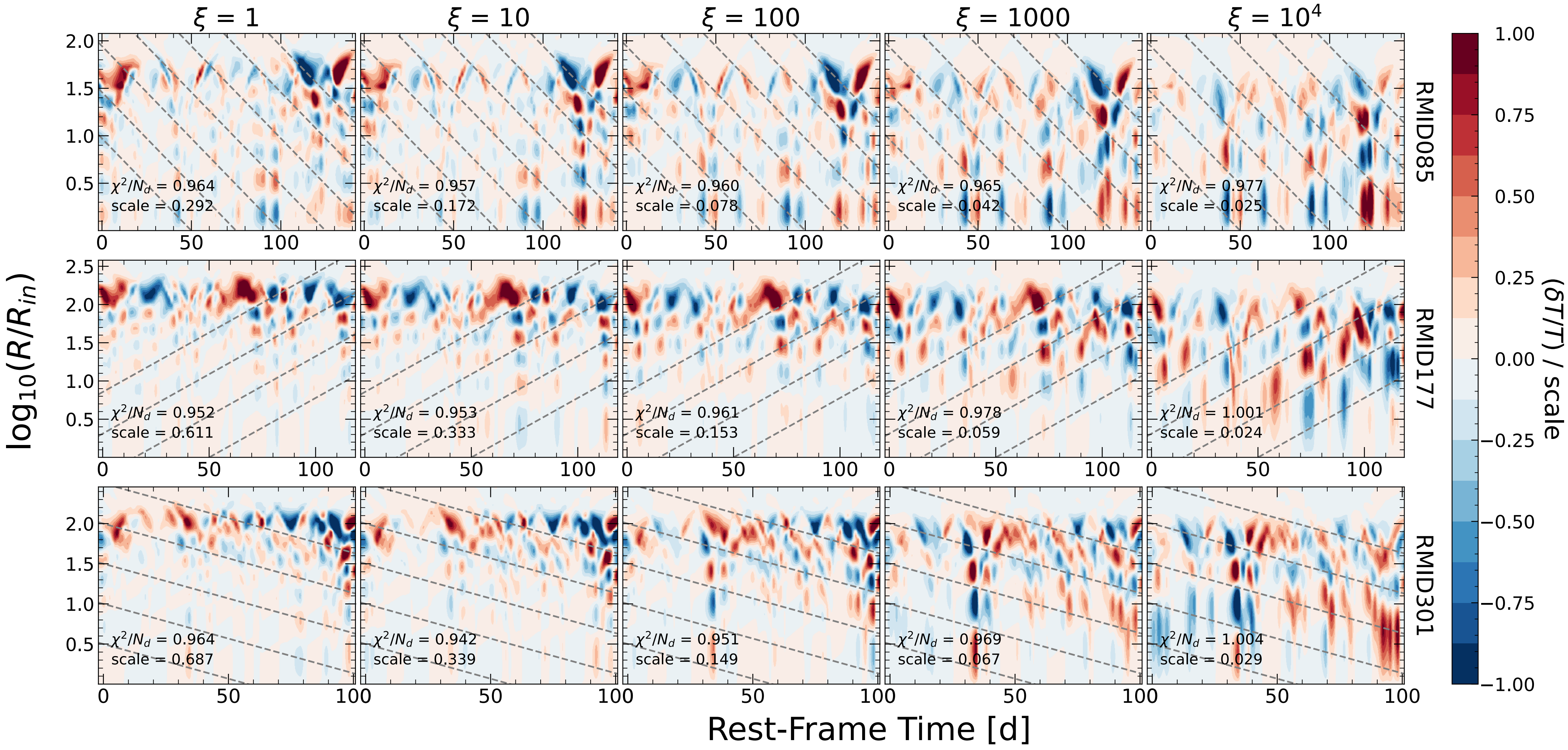
$$t_{\rm th} \equiv (\alpha\Omega)^{-1} = \frac{2c}{\alpha^2\kappa a T^4} = 0.17\alpha^{-2}\,{\rm days}\left(\frac{\kappa}{\kappa_T}\right)^{-1}\left(\frac{T}{2\times10^5{\rm K}}\right)^{-4}$$

Does NOT assume inflow equilibrium, and is independent of black hole mass and accretion rate. α=0.04 implies 100 days.

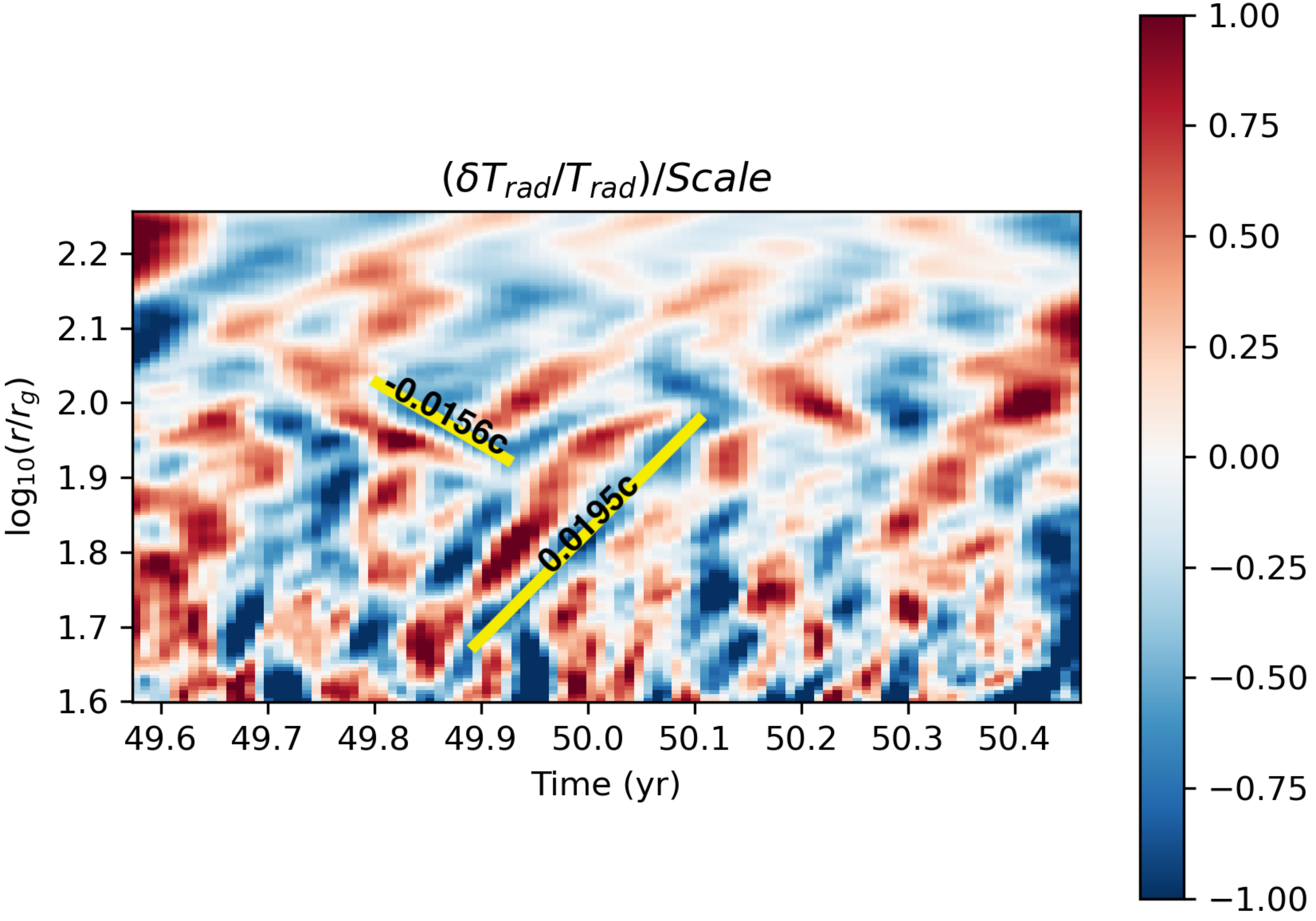
$$t_{\rm sound} \equiv \frac{r}{c_{\rm s}} = r\left(\frac{9\rho}{4aT^4}\right)^{1/2} = \frac{8\pi}{\dot{M}\sqrt{3}}\left(\frac{4GMc^8}{\alpha^5\kappa^8(aT^4)^5}\right)^{1/3}$$

$$= 0.93\alpha^{-5/3}\,{\rm days}\left(\frac{\kappa}{\kappa_T}\right)^{-8/3}\left(\frac{T}{2\times10^5{\rm K}}\right)^{-20/3}\left(\frac{M}{10^8M_\odot}\right)^{-2/3}\left(\frac{\dot{M}}{\eta\dot{M}_{\rm Edd}}\right)^{-1}$$

Propagating Temperature Fluctuations from Reverberation Mapping Campaigns in SDSS Quasars



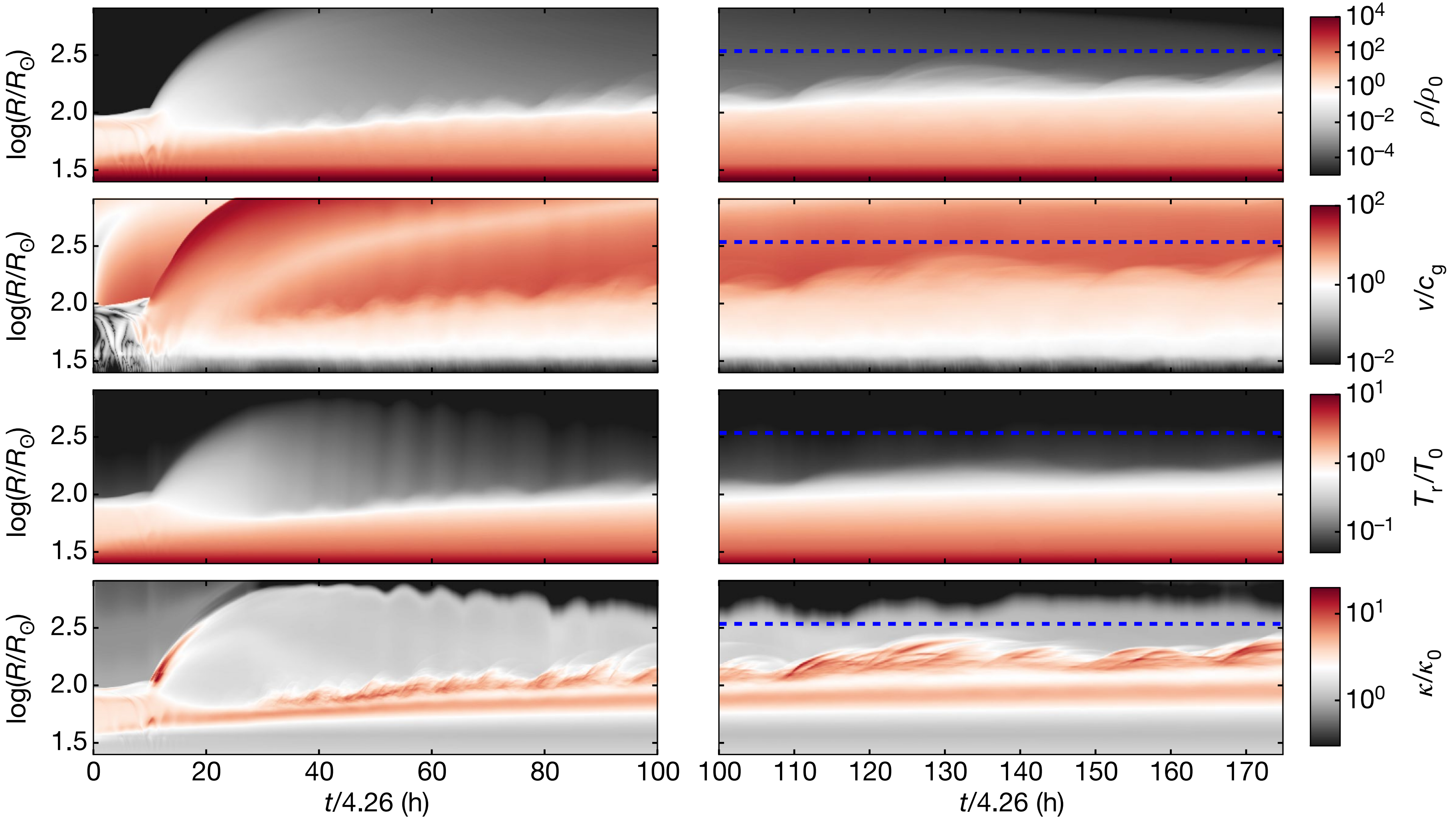
-Stone & Shen 2022 (based on method developed by Neustadt & Kochanek 2022)



Cf. Monday talk
by Papadakis

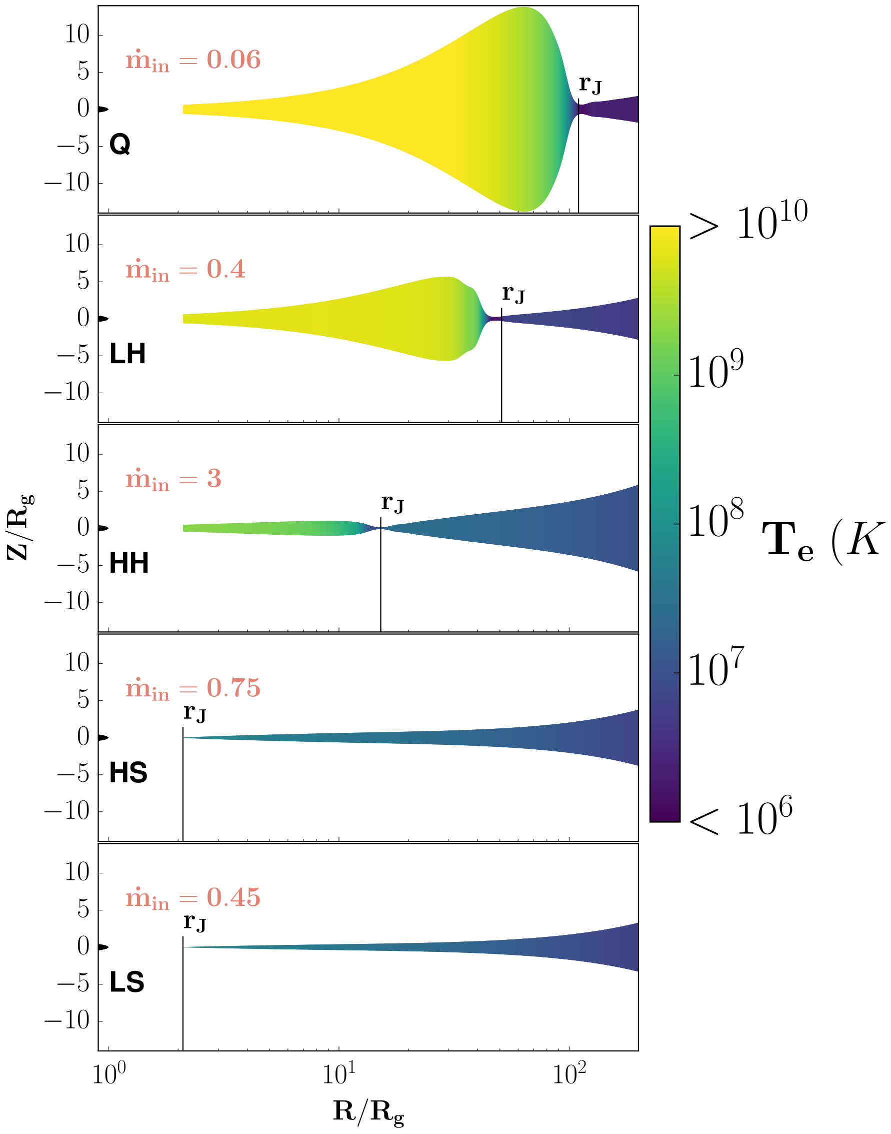
-Plot courtesy of Lunan Sun

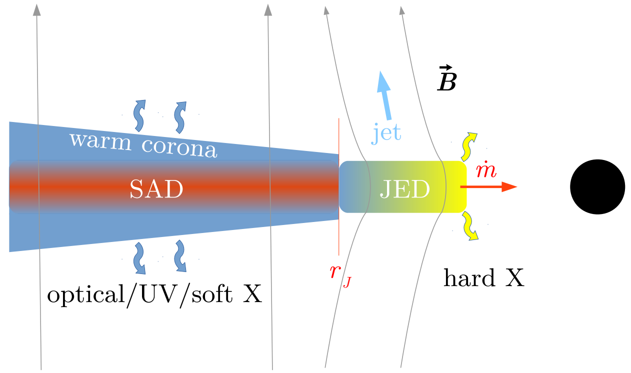
Clumping in Compressible Convection can Trigger the (huge!) Helium Opacity, Driving Outflows
Can We Simulate this in AGN Disks?

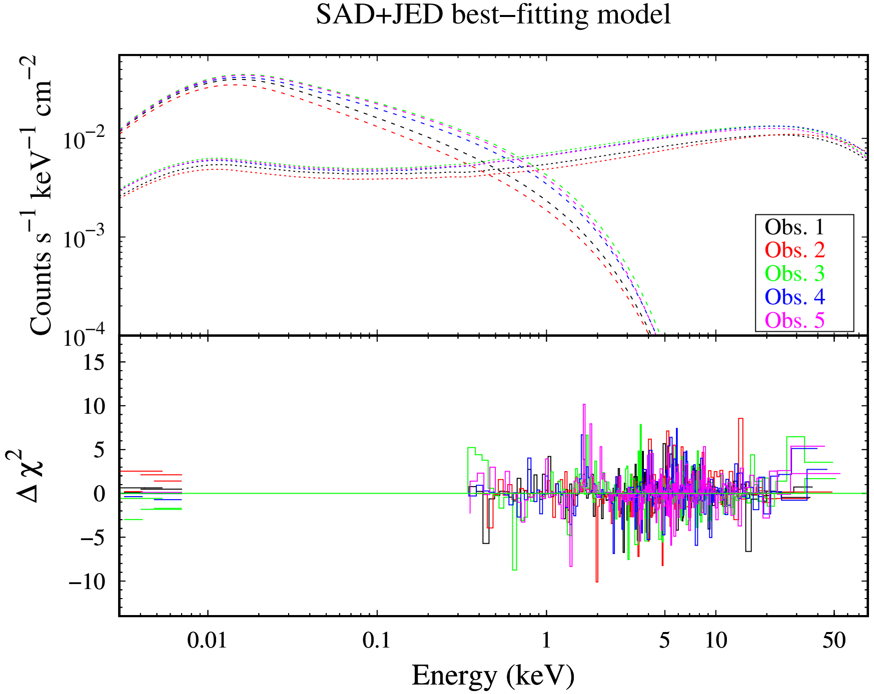


Spherically-averaged quantities from simulation of iron opacity driven convection in a massive star (Jiang et al. 2018)

SAD-JED Model (Ferreira & Pelletier 1995)







-Marcel et al. (2018), as a model for BHXRB states

-Fit to Seyfert 1 HE 1143-1810 (Ursini et al. 2020)

Summary

- The standard Shakura-Sunyaev disk model should not be used, beyond perhaps the trivial scaling of effective temperature with radius.

- Three significant effects must be at work and are currently under active theoretical investigation: **opacity-driven convection** interacting with MRI turbulence, various forms of **magnetically elevated disks**, and **outflows**.

- Iron opacity bump imparts intermittent convection which temporarily 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, and may be a source of acoustic waves in the disk.

- Magnetically elevated disks can show substantial density (and presumably temperature and luminosity variations). It also results in geometrically thicker, less dense (and less self-gravitating) structures with shorter inflow time scales.

- Nobody is yet able to simulate line-driven outflows self-consistently with the (uncertain!) disk structure. Iron opacity might be a mechanism for launching continuum-driven outflows via helium bound-free opacity.