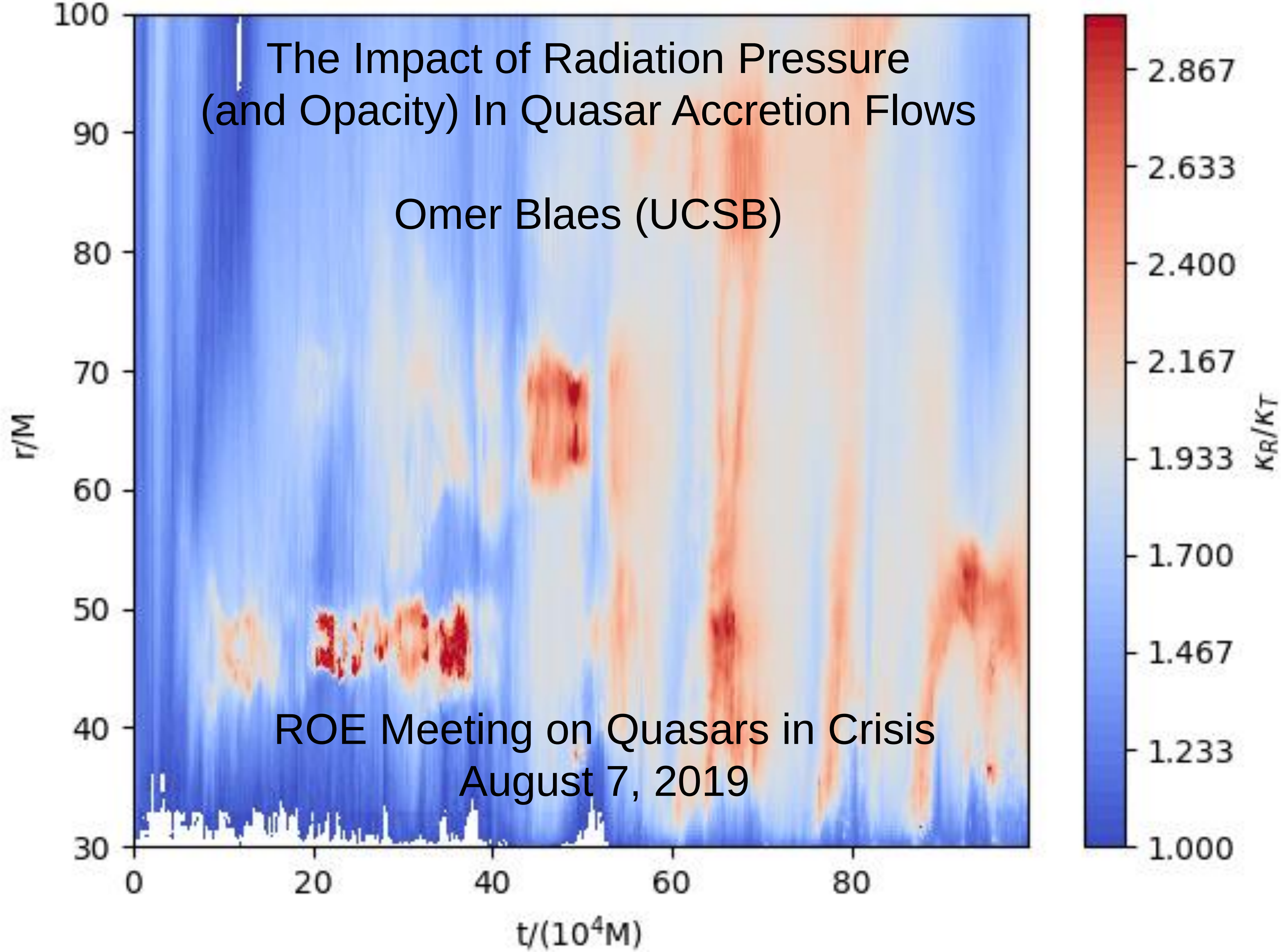
The Impact of Radiation Pressure (and Opacity) In Quasar Accretion Flows

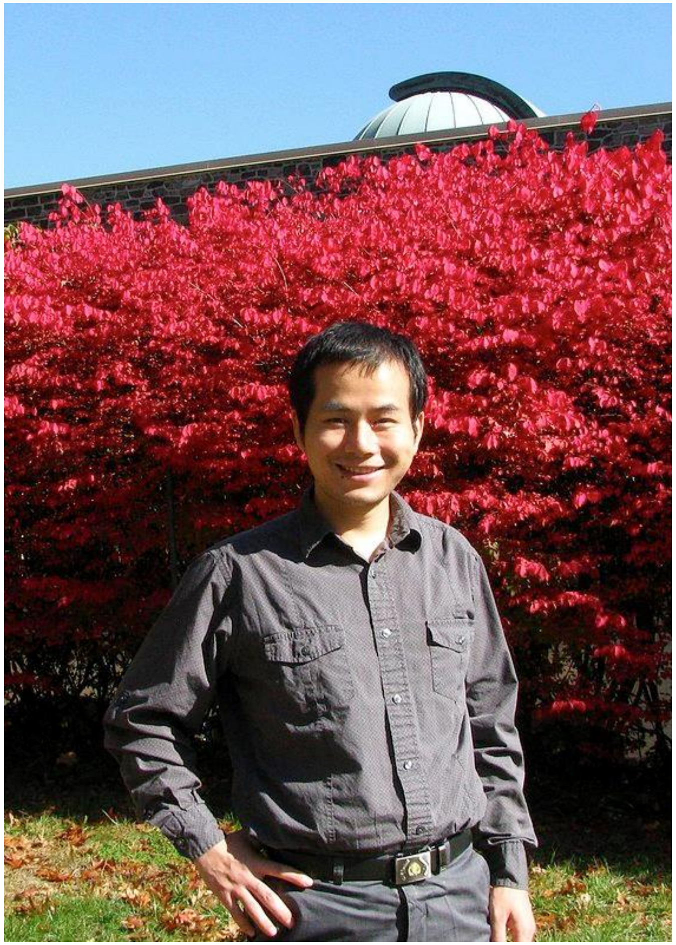
Omer Blaes (UCSB)

ROE Meeting on Quasars in Crisis
August 7, 2019



Collaborators

- Shane Davis (Virginia)
- Yan-Fei Jiang 姜燕飞 (UCSB/KITP)
- Jim Stone (Princeton)



Importance of Radiation Pressure in Luminous AGN

We do not really know the flow structure, so just assume the following

$$L \sim L_{\mathrm{Edd}} = \frac{4\pi GMc}{\kappa}, \quad H \sim r, \quad |\mathrm{v}_r| = \alpha\sqrt{\frac{GM}{r}}, \quad r \sim \frac{GM}{c^2}$$

(Rees 1984)

$$\dot{M} \sim 4\pi r^2 \rho |\mathrm{v}_r|$$ Local mass flux

$$L \sim \frac{GM\dot{M}}{r}$$ Radiatively efficient

$$L \sim \frac{4\pi r^2 caT^4}{\tau} \sim \frac{4\pi rcaT^4}{\kappa\rho}$$ Diffusive photon transport (problematic, as we will see later)

Then

$$\rho \sim \frac{c^2}{GM\kappa\alpha} \sim 2\times 10^{-13}\,\mathrm{g\,cm^{-3}}\left(\frac{M}{10^8 M_{\mathrm{sun}}}\right)^{-1}\left(\frac{\kappa}{\kappa_{\mathrm{T}}}\right)^{-1}\alpha^{-1}$$

$$T \sim \left(\frac{c^4}{GMa\kappa\alpha}\right)^{1/4} \sim 4\times 10^5\,\mathrm{K}\left(\frac{M}{10^8 M_{\mathrm{sun}}}\right)^{-1/4}\left(\frac{\kappa}{\kappa_{\mathrm{T}}}\right)^{-1/4}\alpha^{-1/4}$$

$\tau \sim \alpha^{-1}$ (Also effectively thin for free-free/Thomson)

$$\frac{P_{\mathrm{rad}}}{P_{\mathrm{gas}}} \sim \frac{\mu c}{3k}(GMa\kappa\alpha)^{1/4} \sim 5\times 10^6\left(\frac{M}{10^8 M_{\mathrm{sun}}}\right)^{1/4}\left(\frac{\kappa}{\kappa_{\mathrm{T}}}\right)^{1/4}\alpha^{1/4}$$

Cf. standard thin disk theory (which should not be applied to AGN!)

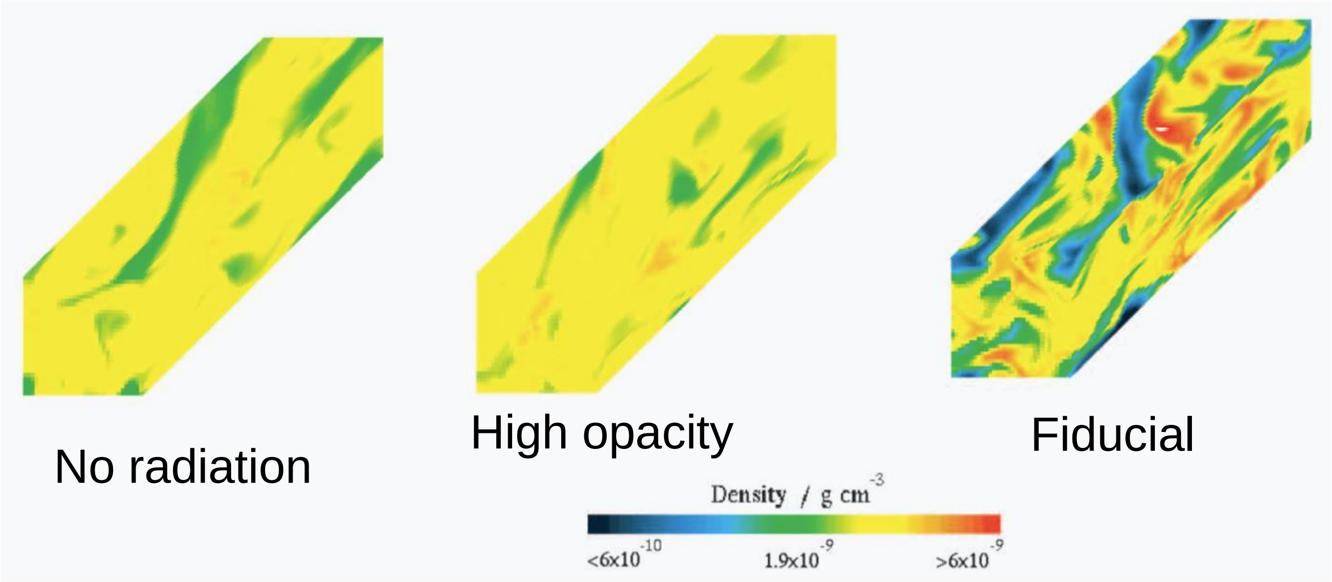
$$\frac{P_{\mathrm{rad}}}{P_{\mathrm{gas}}} \approx 10^7 \alpha^{1/4}(1-f)^{9/4}\left(\frac{M}{10^8 M_{\mathrm{sun}}}\right)^{1/4}\eta^{-2}\left(\frac{L}{L_{\mathrm{Edd}}}\right)^{2}\left(\frac{r}{r_{\mathrm{g}}}\right)^{-21/8}$$

(Some) Physics Issues Associated with Radiation Pressure

- Density Inhomogeneities and Radiation Damping
- Overcoming Photon Trapping
- Thermal Instability
- Outflows
- Radiation Viscosity and Bulk Comptonization
- Very high sensitivity to opacities (Davis' talk)

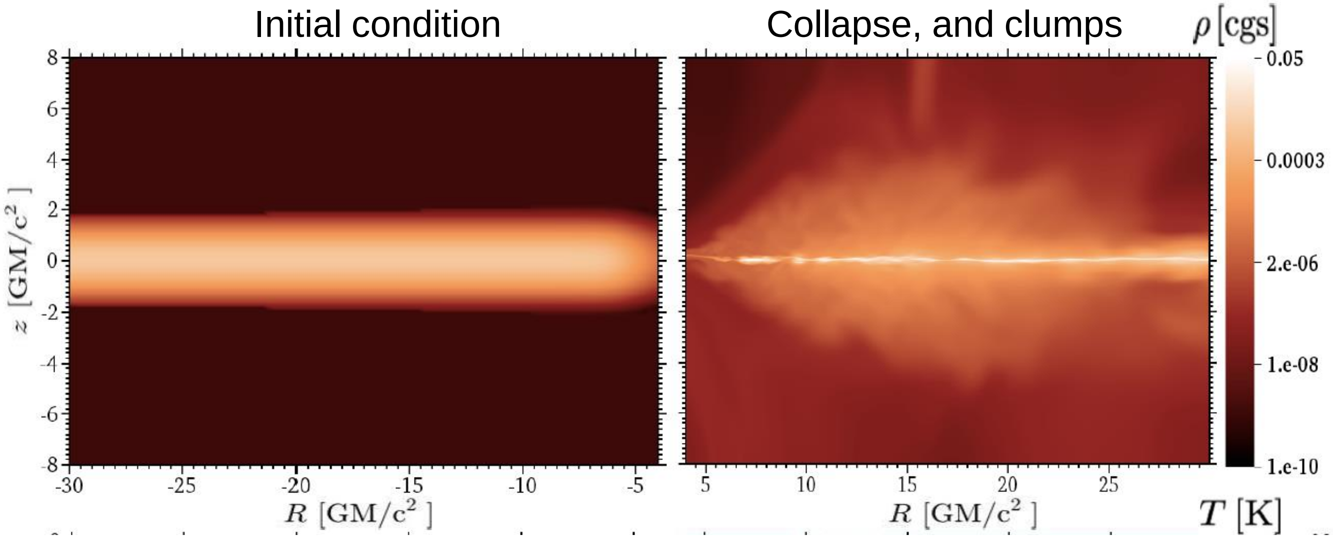
Radiation Dominated Plasmas are Prone to Inhomogeneities

$$P = \frac{1}{3} a T^4$$

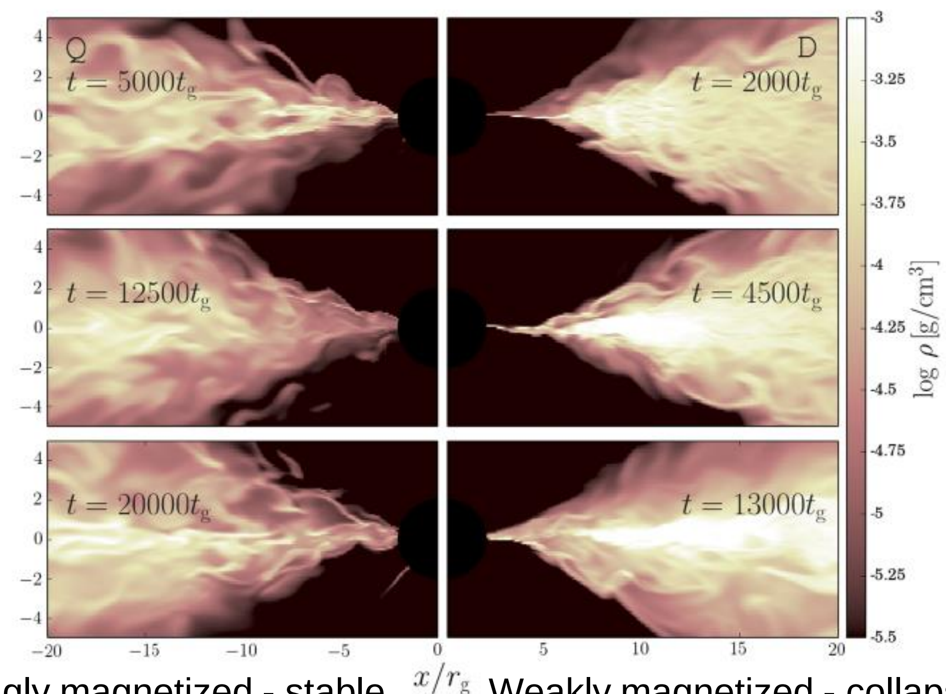


-MRI simulations by Turner et al. (2003)

Global GRMHD Simulations of Thermal/Viscous Instability



-Mishra et al. (2016)



Strongly magnetized - stable

Weakly magnetized - collapses

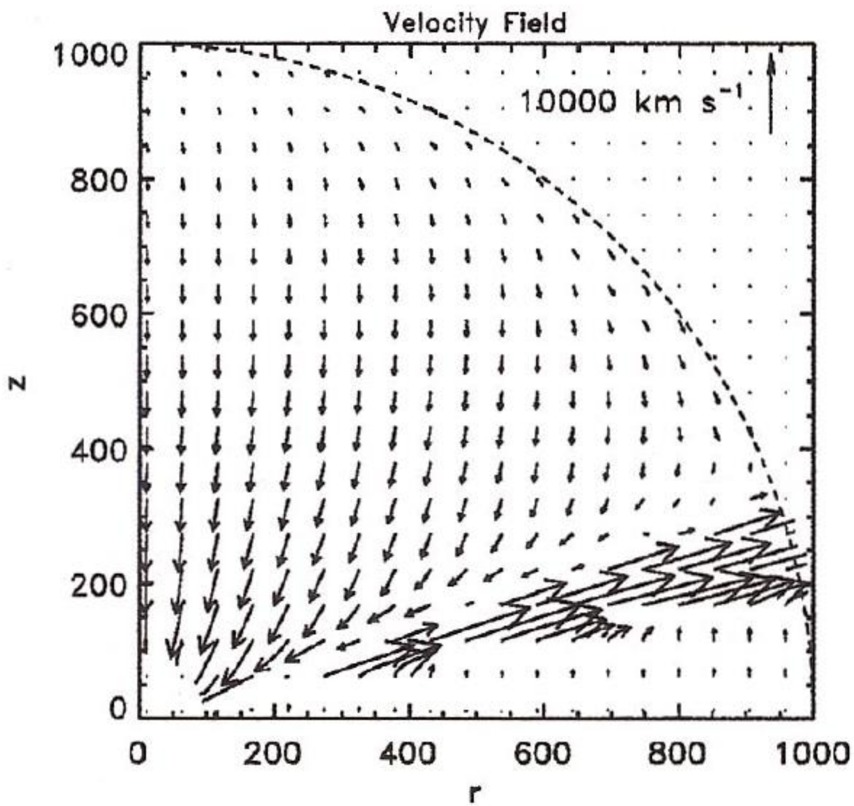
-Sadowski (2016)

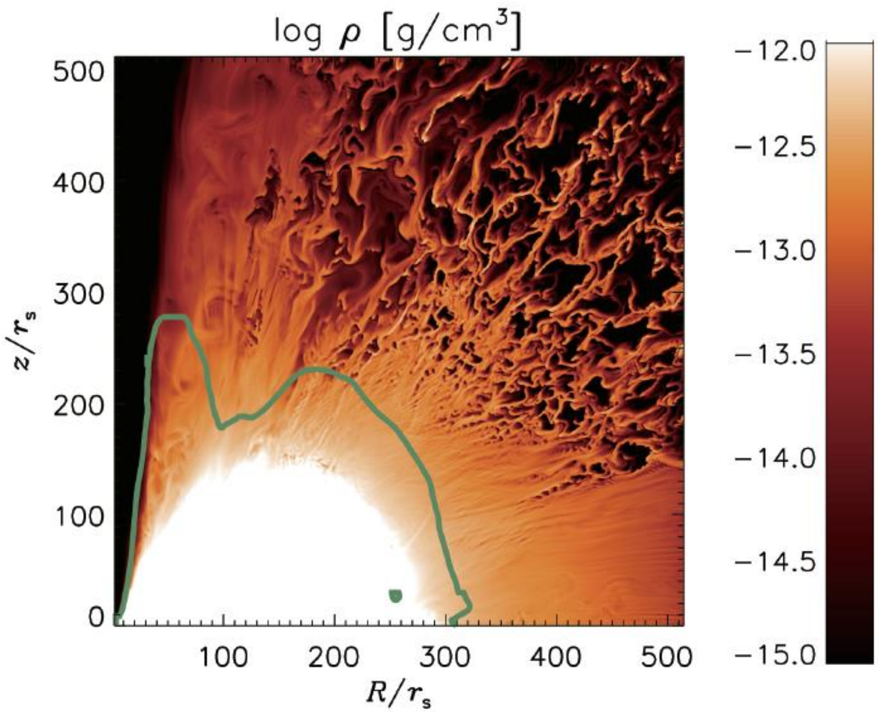
Thermal Instability

Magnetically pressure supported disks can be stabilized (Sadowski 2016). How magnetized are AGN disks?

Iron opacity bump can stabilize certain radial ranges of AGN accretion disks (Jiang, Davis & Stone 2016) by giving an optical depth that declines with temperature and by enhancing radiation advection.

Outflows





-Proga, Stone & Kallman (2000)

-Takeuchi, Ohsuga, & Mineshige (2013)

-Explains the universal 1000 angstrom break (Laor & Davis 2014).

Turbulent Comptonization vs. Thermal Comptonization (Socrates et al. 2004, Socrates 2010)

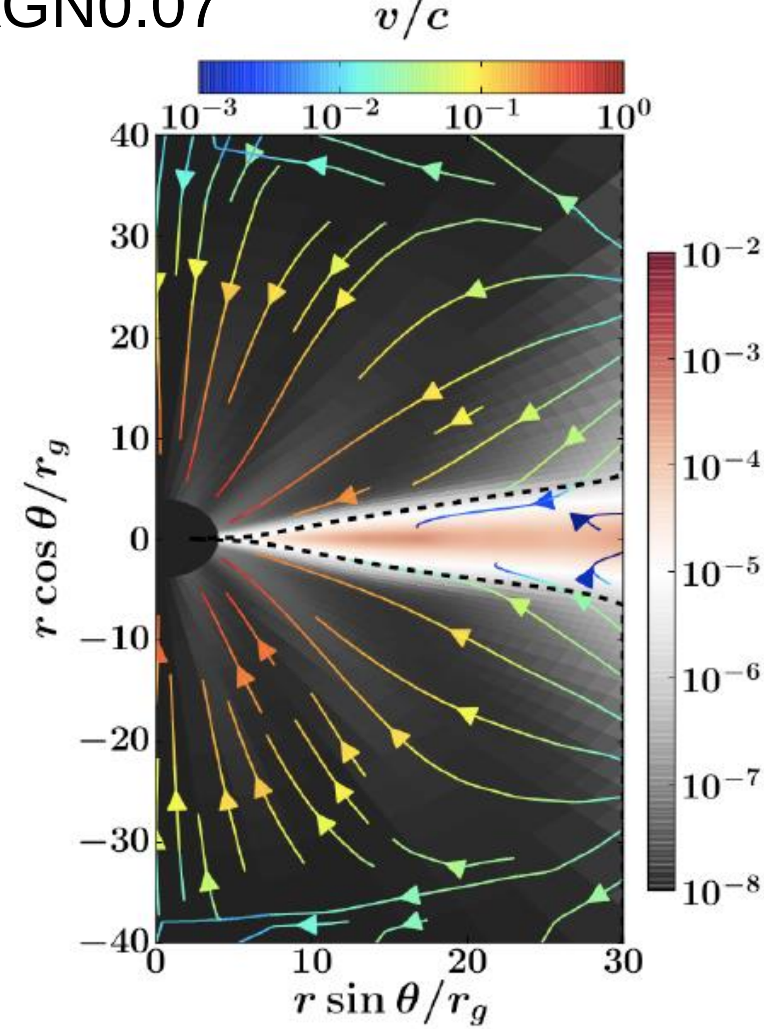
$$< v_e^2 >^{1/2} = \left(\frac{3kT}{m_{\rm e}}\right)^{1/2} \sim \left(\frac{P_{\rm gas}}{\rho}\right)^{1/2}\left(\frac{m_{\rm p}}{m_{\rm e}}\right)^{1/2} \sim c_{\rm gas}\left(\frac{m_{\rm p}}{m_{\rm e}}\right)^{1/2}$$

$$v_{\rm turb} \sim v_{\rm A} \sim \left(\frac{P_{\rm mag}}{P_{\rm rad}}\right)^{1/2}\left(\frac{P_{\rm rad}}{P_{\rm gas}}\right)^{1/2} c_{\rm gas}$$

Radiation viscosity (Loeb & Laor 1992, Kaufman & Blaes 2016)

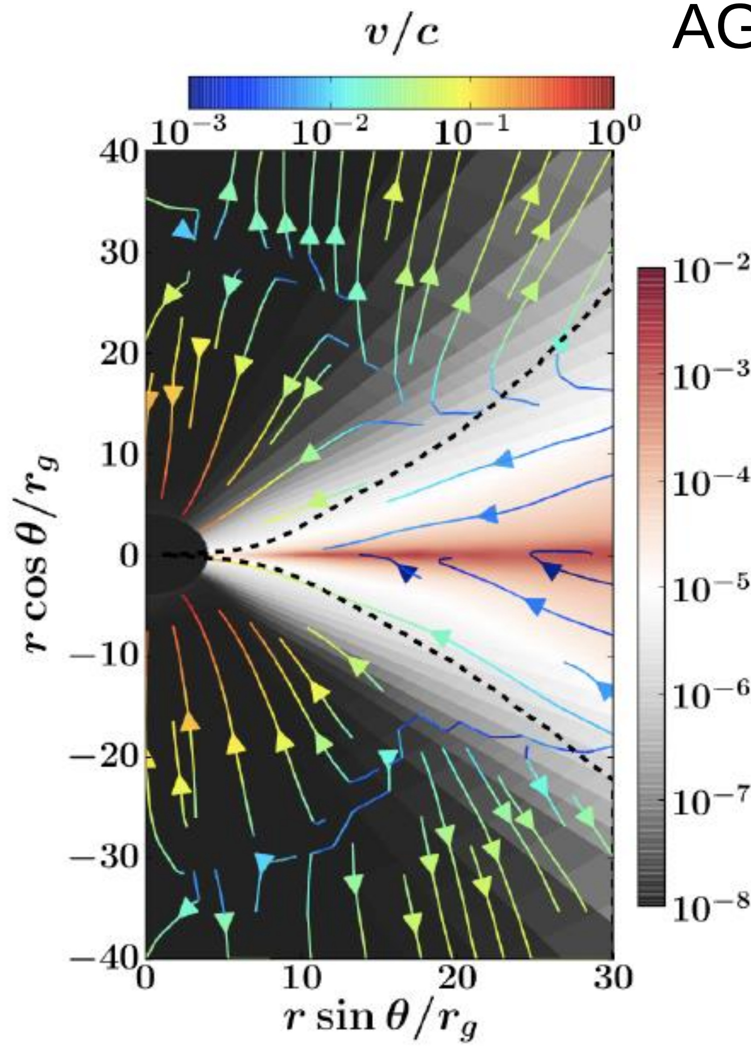
Radiation MHD Simulations of Sub-Eddington Accretion

AGN0.07



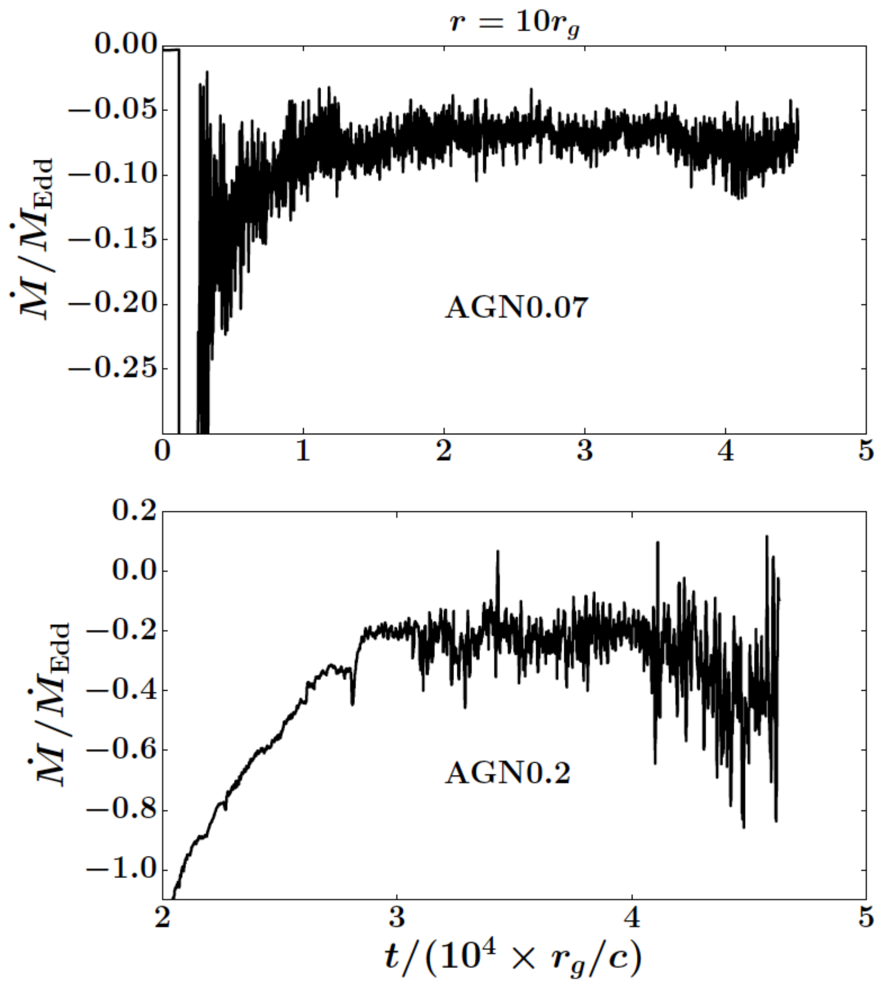
Initialized with two poloidal loops,
with net radial magnetic field in midplane

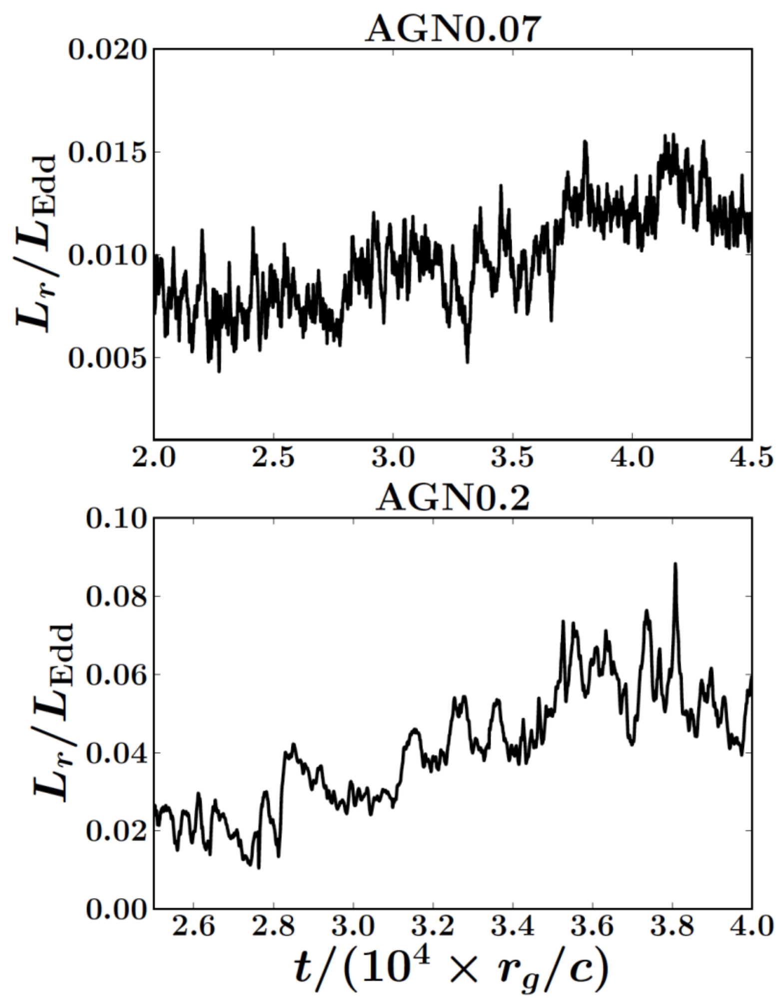
AGN0.2



Initialized with stronger, single poloidal loop

-Jiang, Blaes, Stone, & Davis (2019)



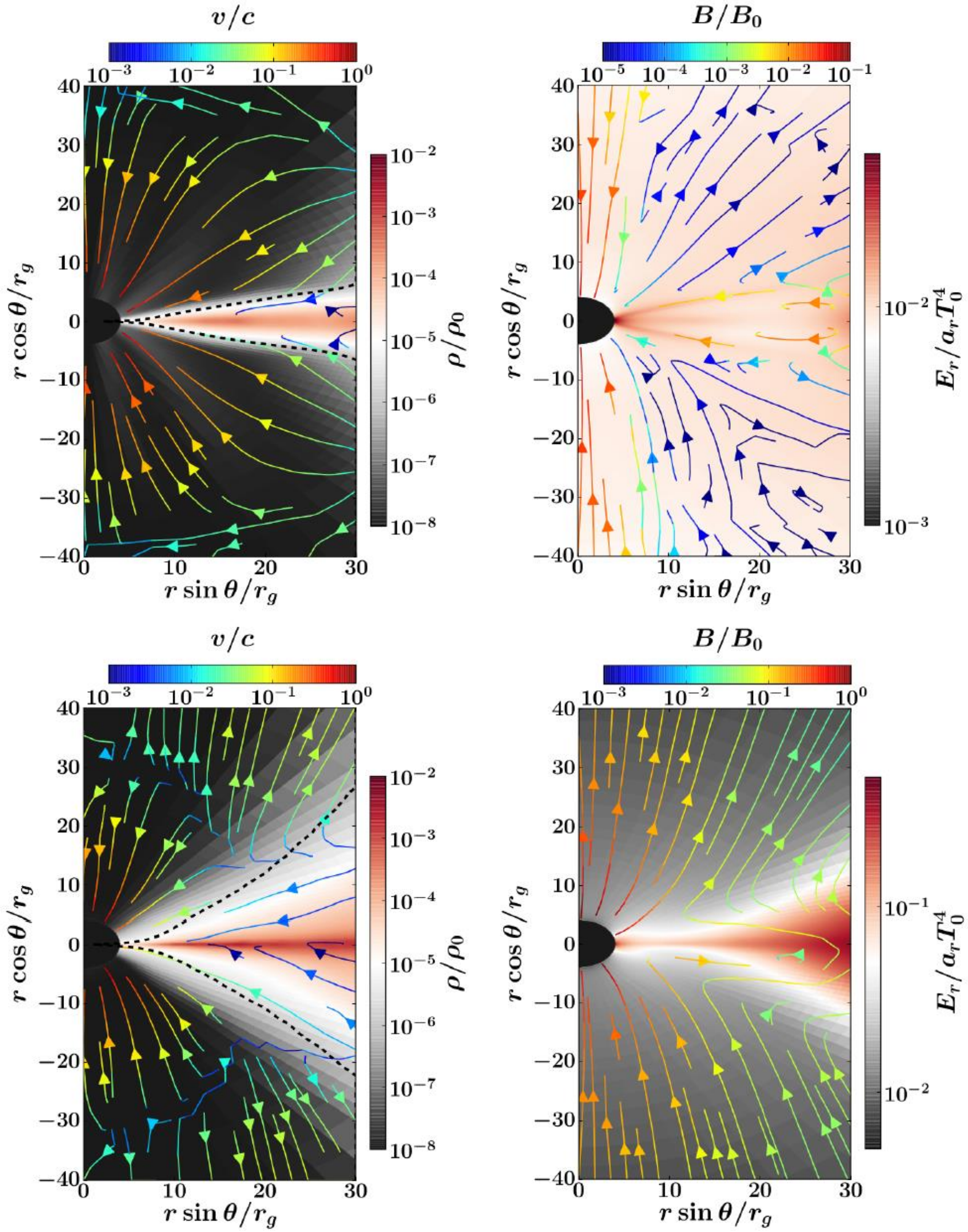


Time unit = 0.78 years

Density Radiation Energy Density

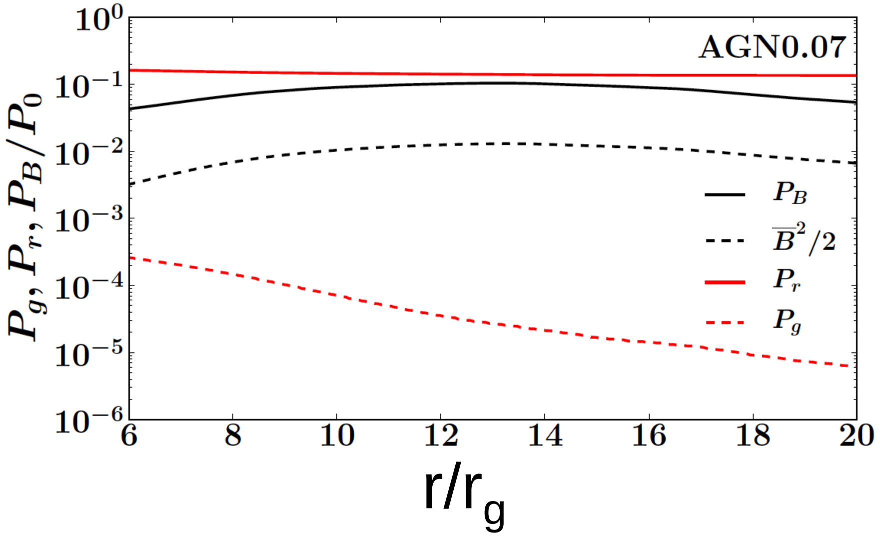
AGN0.07

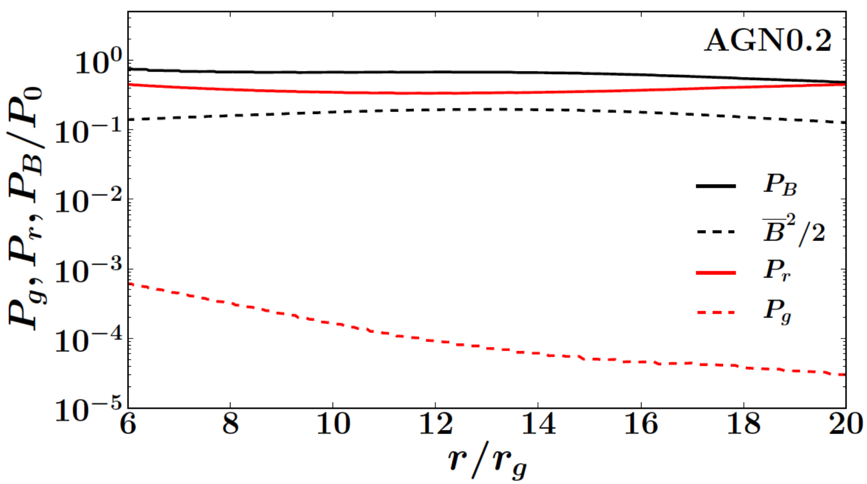
AGN0.2



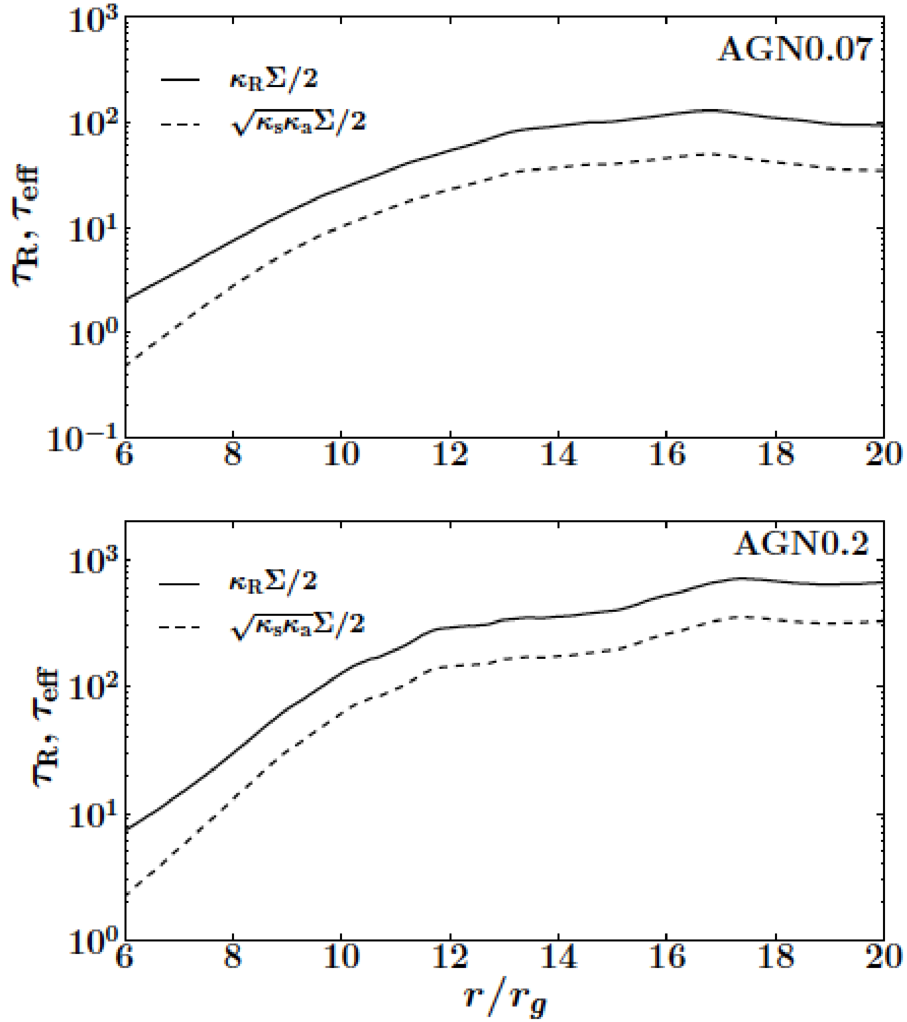
No thermal runaway!

Magnetic Pressure is Just as Important as Radiation Pressure In Inner Regions of Disk, which Might Explain Thermal Stability

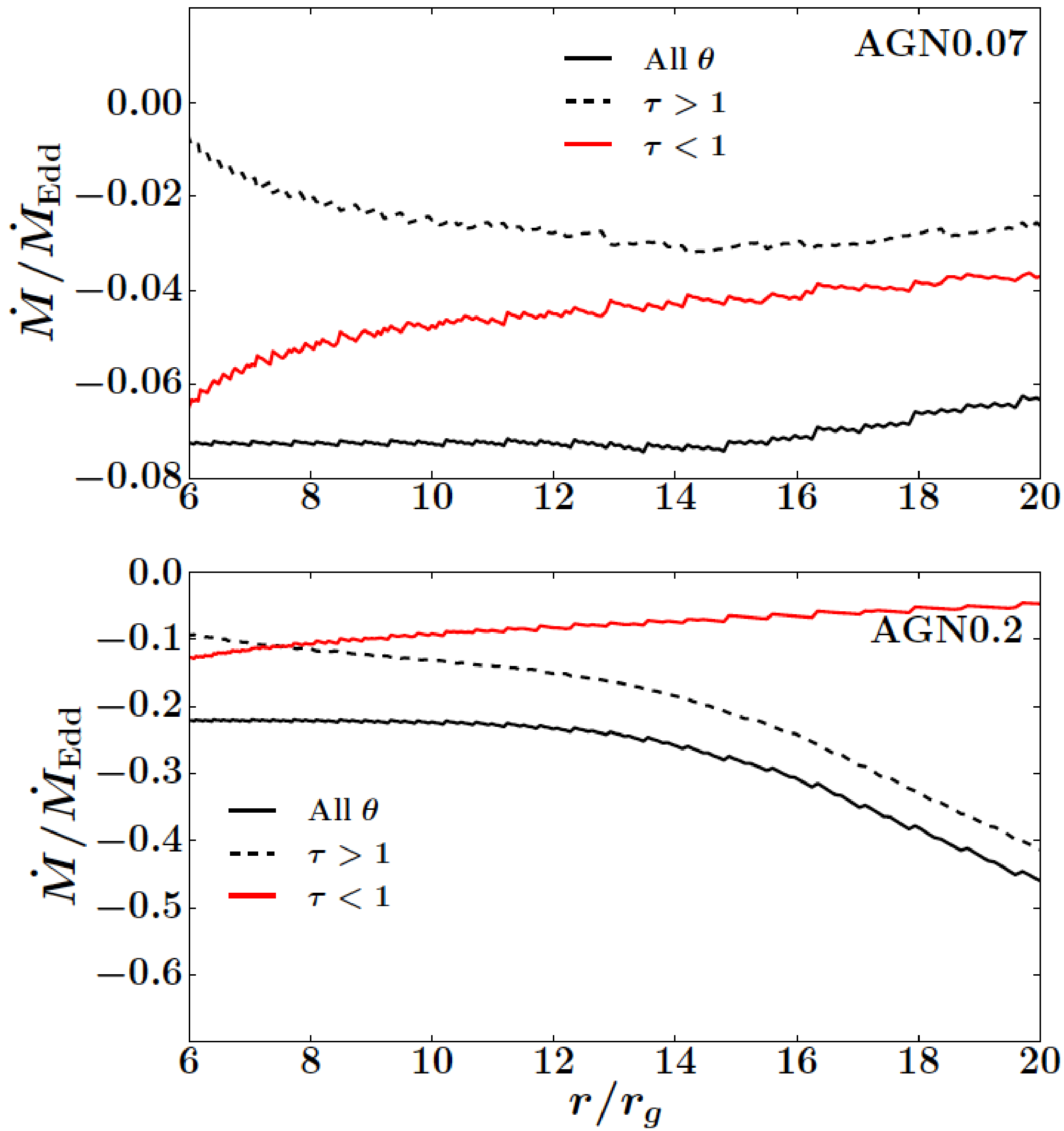




Effective and Scattering Optical Depth Variation with Radius



More effectively thin at lower Eddington ratio!

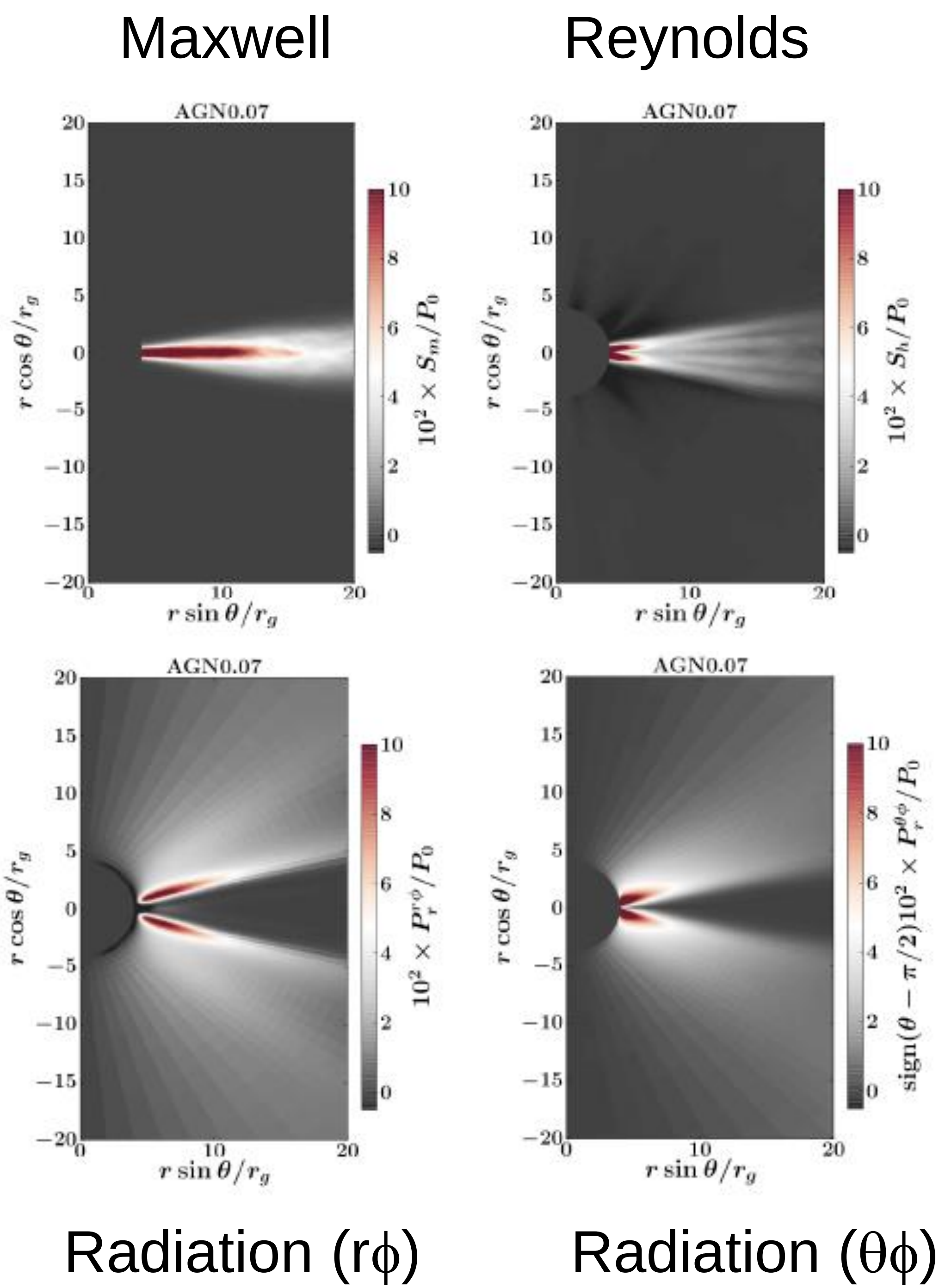


Surface accretion!
(cf. Zhu & Stone 2018,
Mishra et al. 2019)

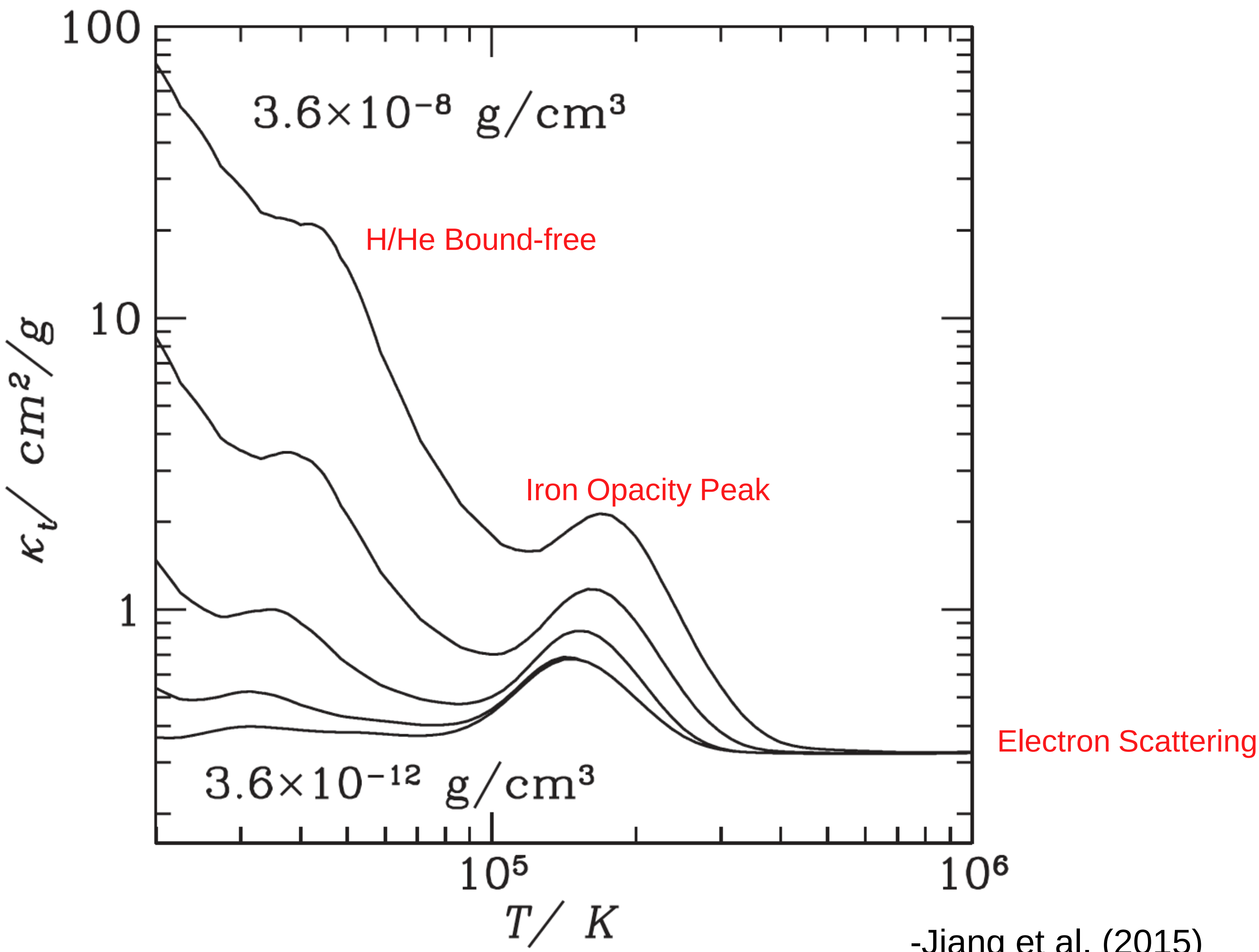
Midplane
accretion

Disk midplane is dominated by Maxwell and Reynolds stresses.

Disk surface layers are dominated by radiation viscosity, and these dominate the vertical average.

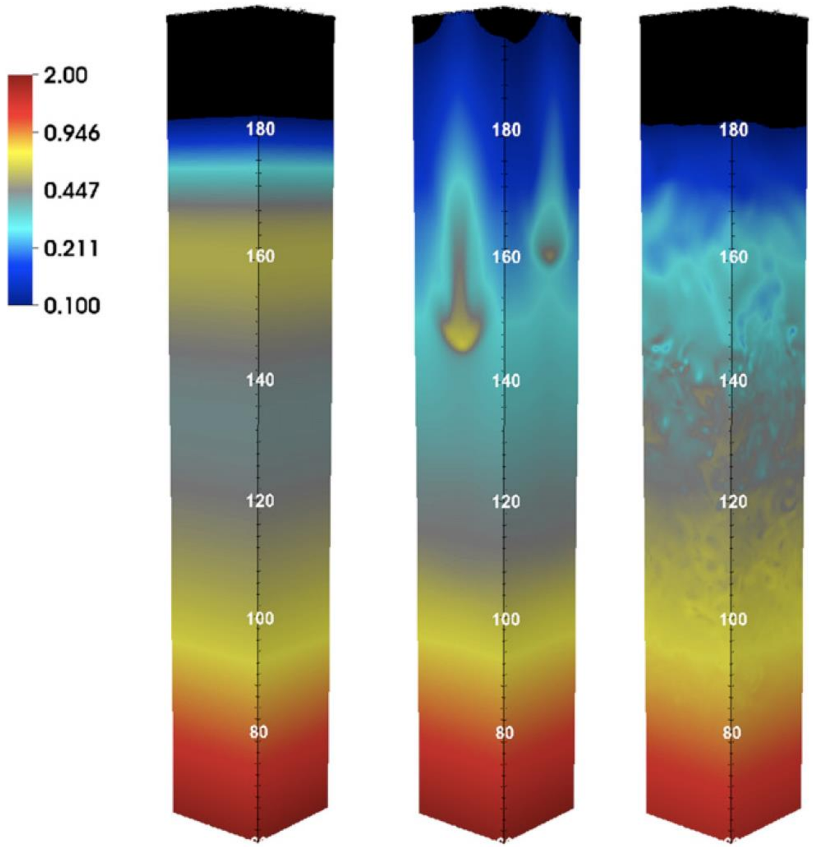


Rosseland Opacity under Massive Star (or AGN) Conditions

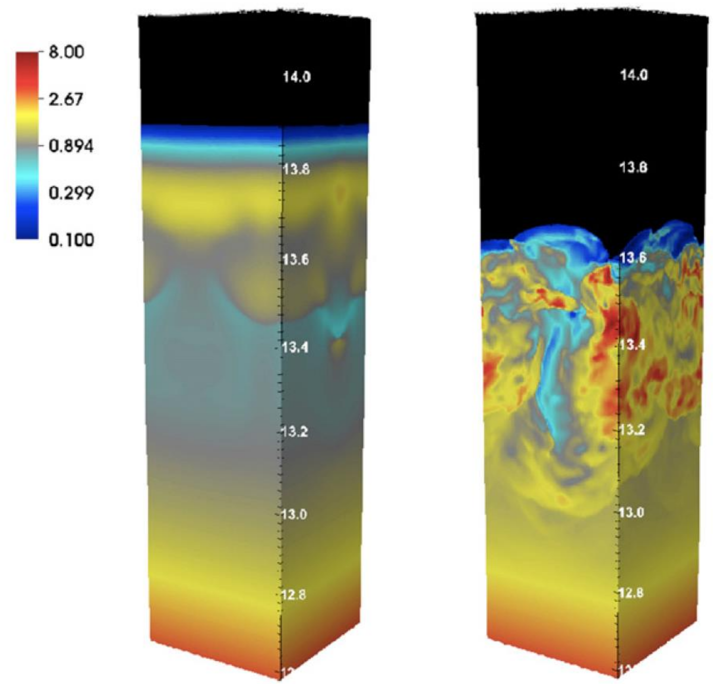


-Jiang et al. (2015)

Iron Opacity Effects in Massive Stars



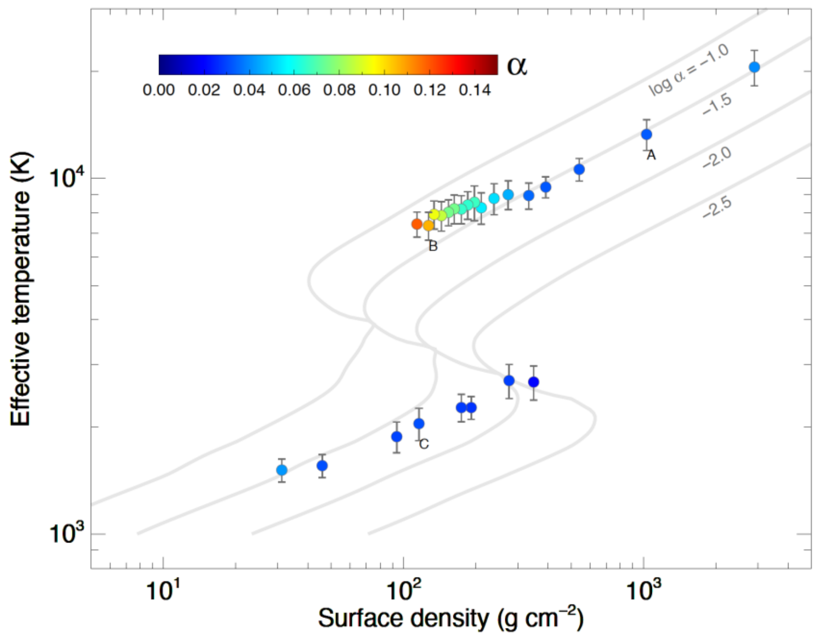
Slow photon diffusion:
density inversion wiped out
and convection is efficient.



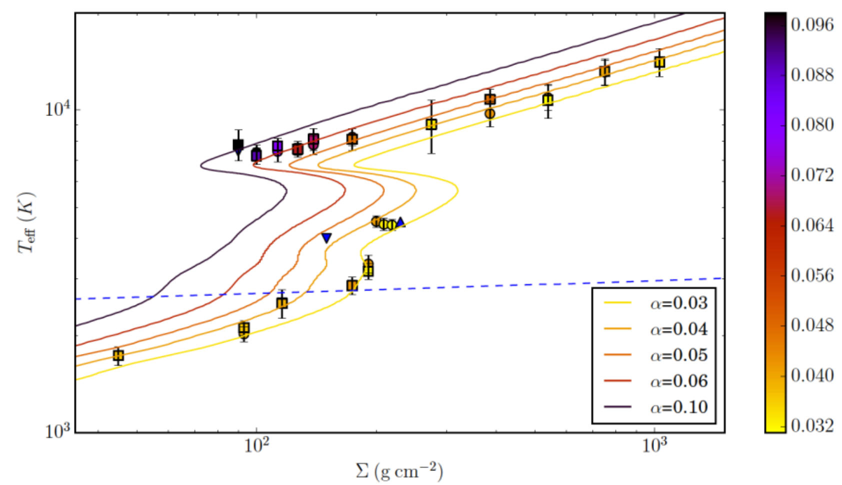
Rapid photon diffusion:
strong turbulence results in
porous medium. Density inversion is
maintained in time/space average.

-Jiang et al. (2015)

Vertically Stratified Shearing Boxes in the Hydrogen-Ionization Regime



-Hirose et al. (2014)
(ZEUS)

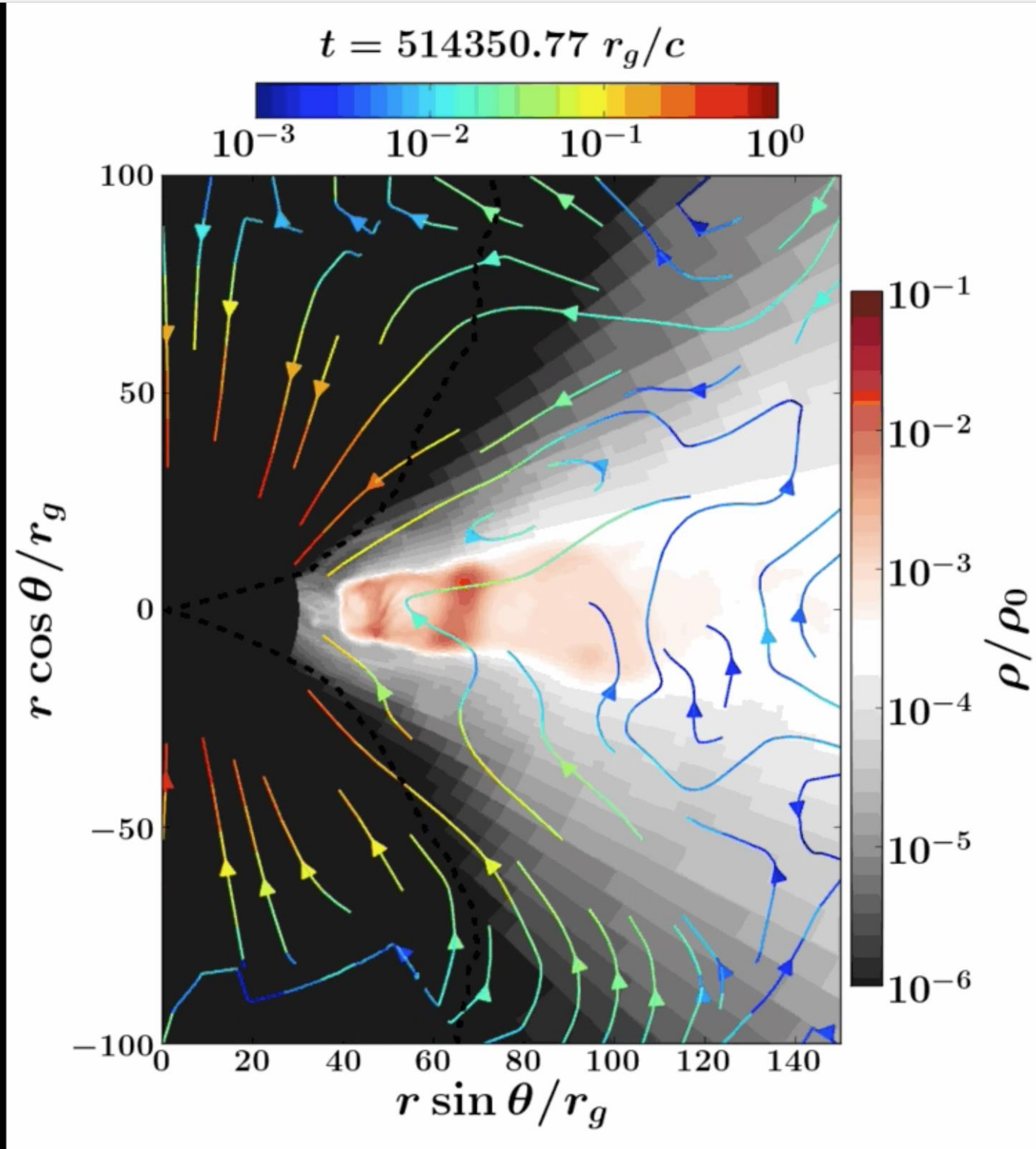


-Scepi et al. (2018)
(PLUTO)

-Convection can enhance the turbulent stress to pressure ratio in these gas pressure dominated white dwarf accretion disks.

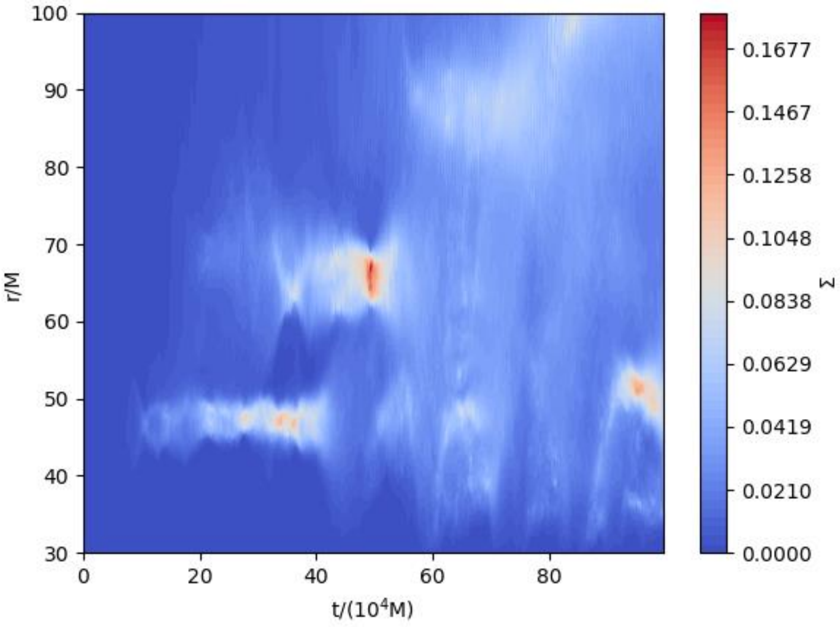
OK – so what happens when we combine radiation pressure with the iron opacity peak?

The following is a PRELIMINARY simulation in which the inner 30 gravitational radii are cut out. We have not succeeded in achieving inflow equilibrium (does such a thing exist?), but it illustrates the potential complex behavior and variability.
(Jiang, Blaes, Davis, and Stone, in prep).

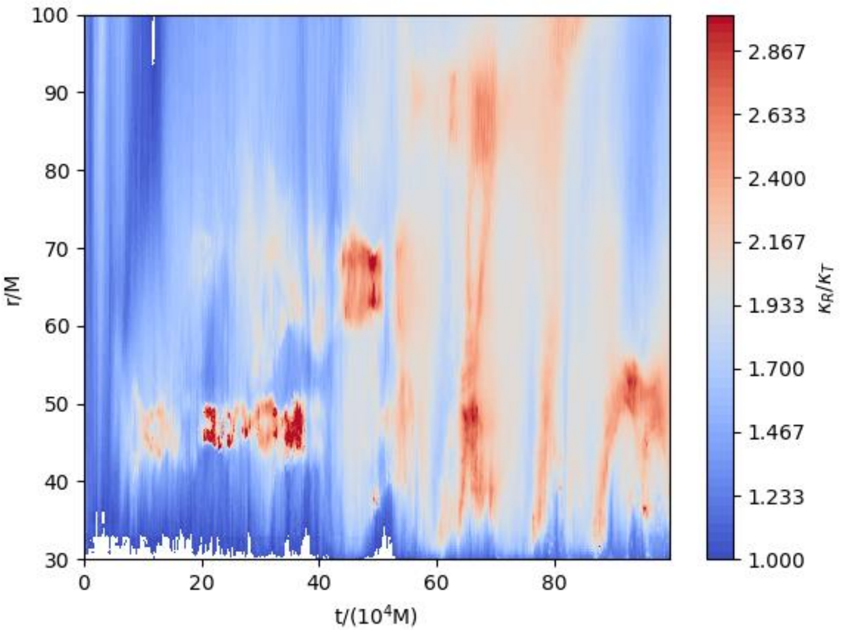


$t = 514350.77\ r_g/c$
10^{-3} 10^{-2} 10^{-1} 10^{0}
$r \cos\theta / r_g$
$r \sin\theta / r_g$
ρ/ρ_0
10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6}
100 50 0 −50 −100
0 20 40 60 80 100 120 140

Surface density

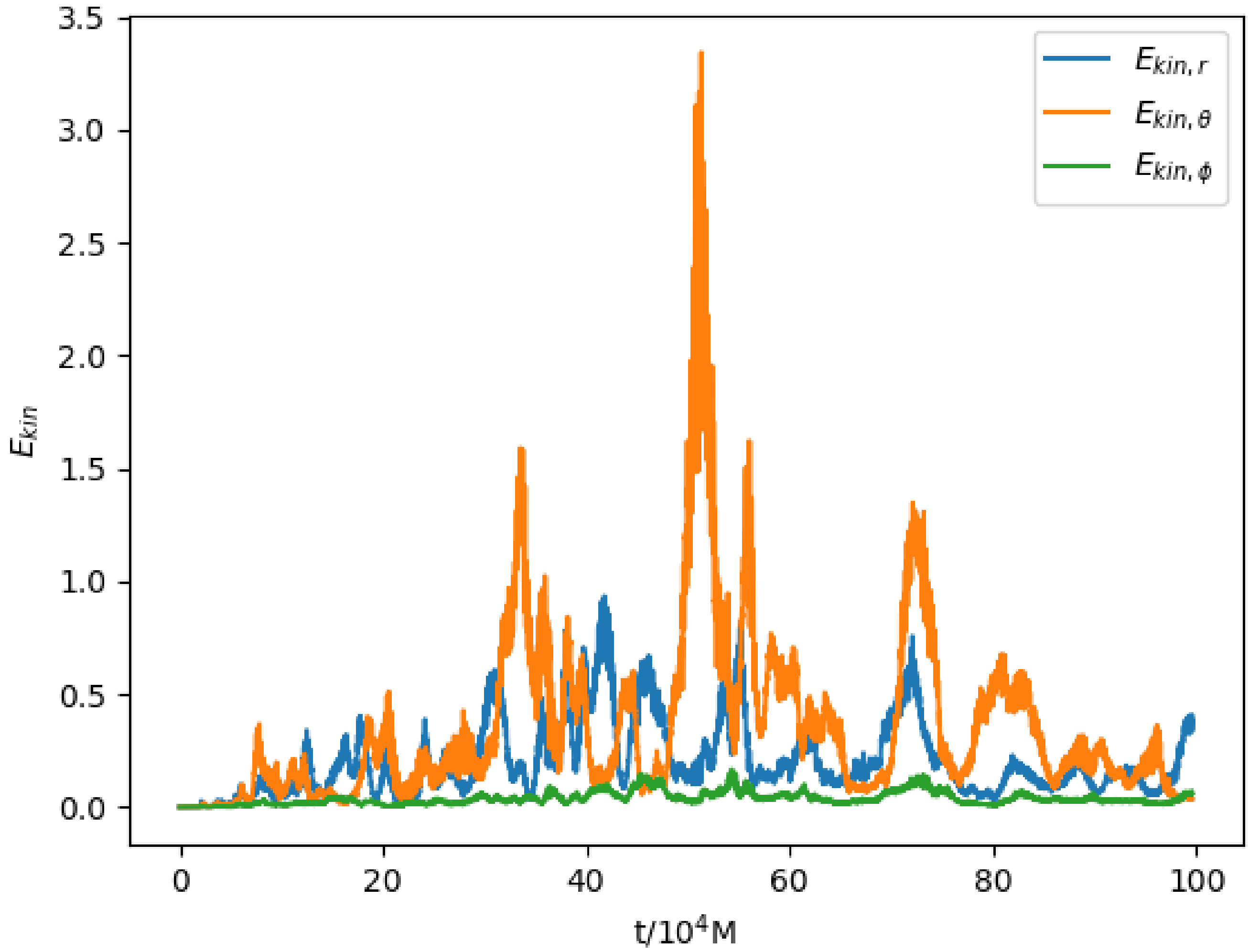


Opacity



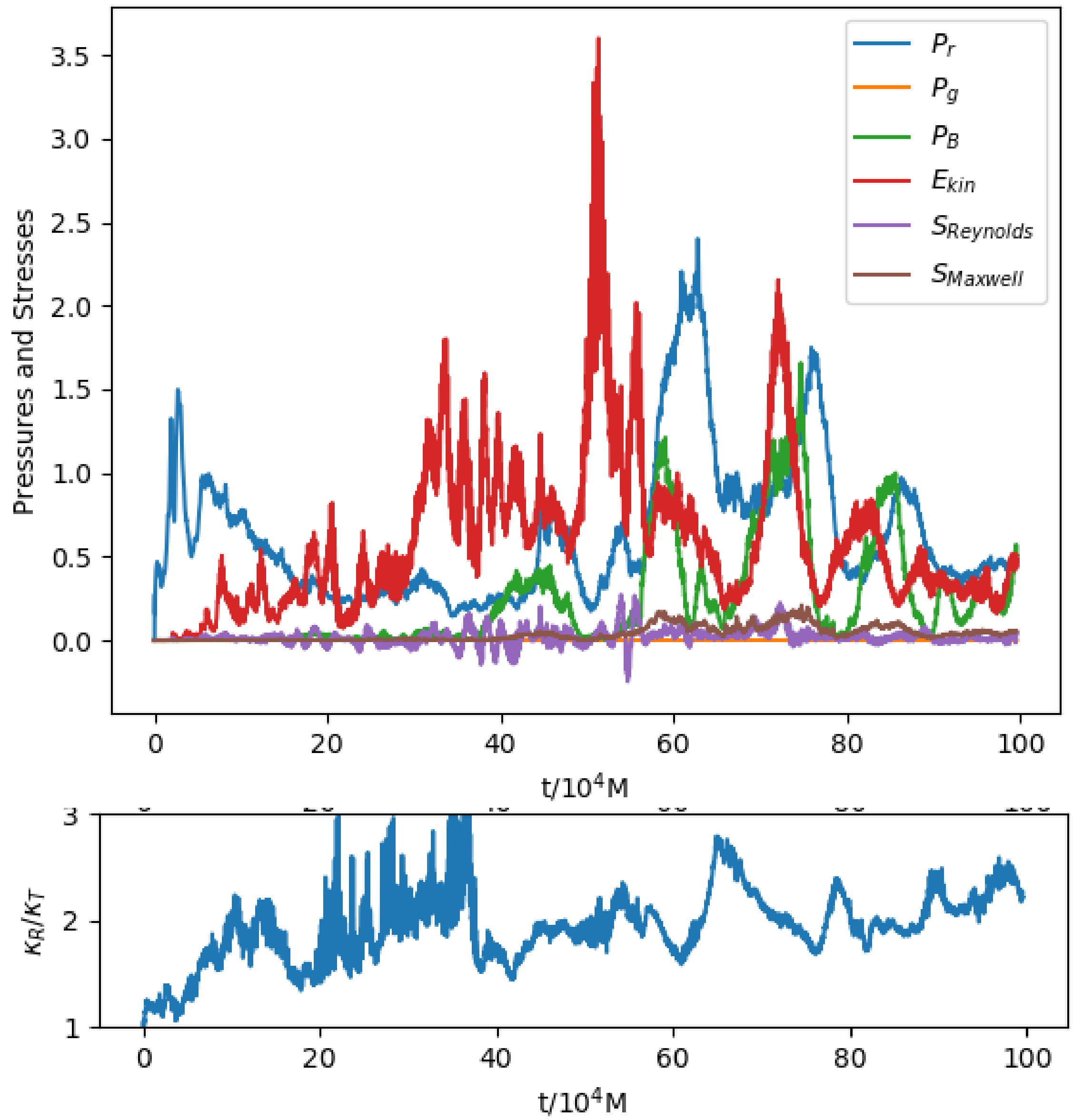
(Time of 10^4M=0.78 years)

Turbulent kinetic energy is mostly poloidal (and vertical), i.e. driven by convection, not MRI motions.

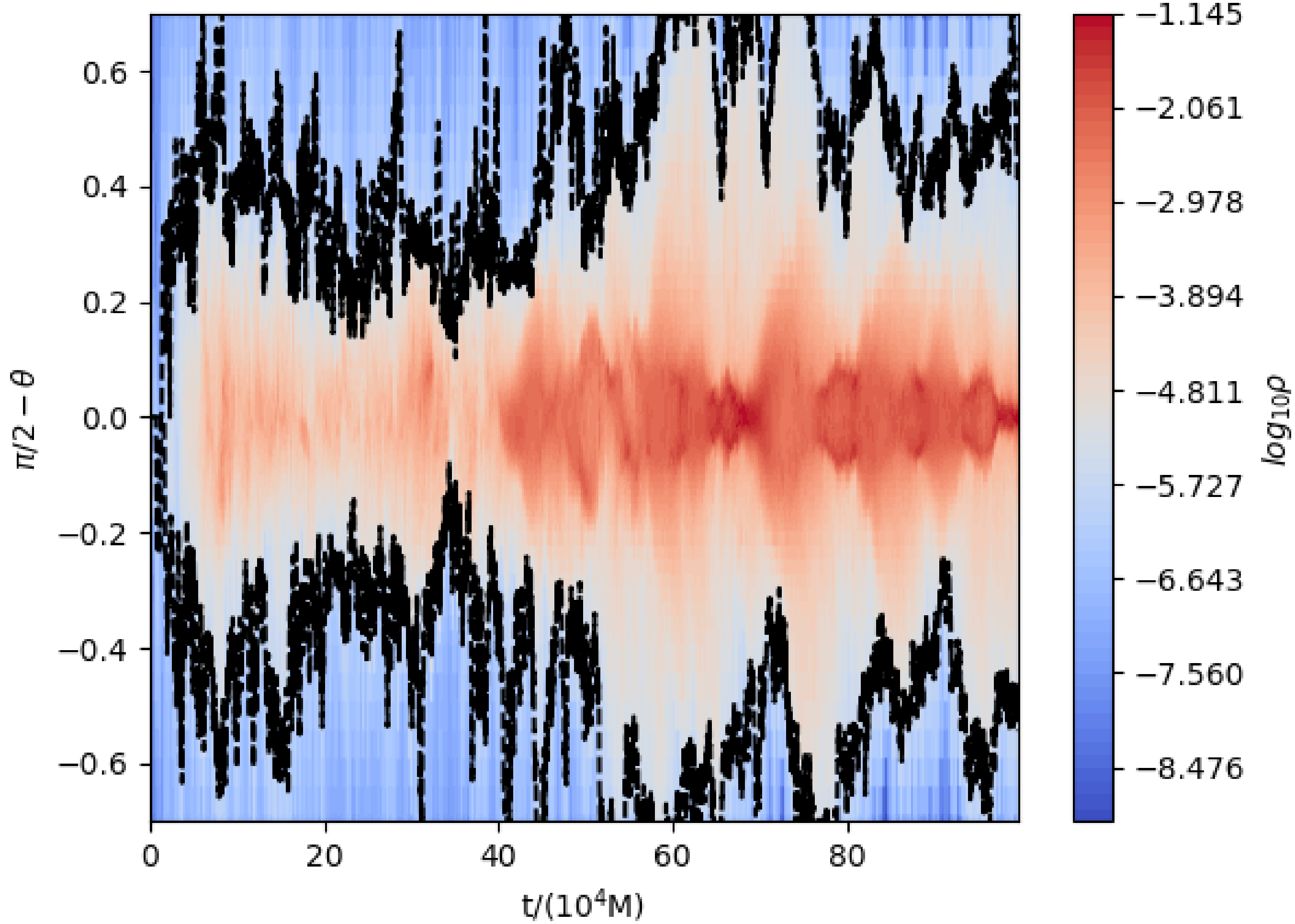


$r=47r_g$

Variability of Various Pressures and Energy Densities at 47 r_g

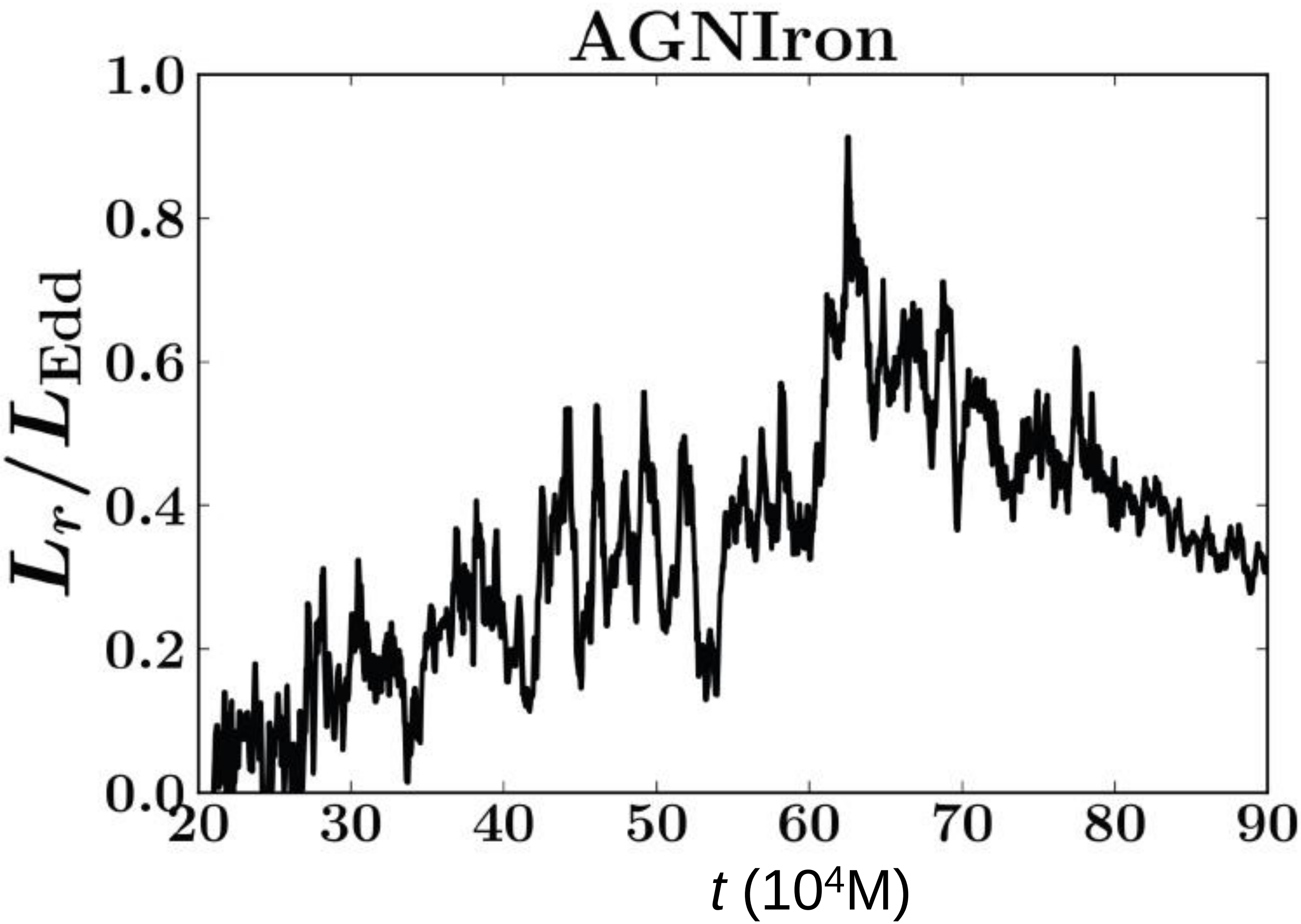


Substantial Vertical Density Inversions are Sustained in the Convection



$r=40r_g$

Lightcurve (missing inner 30 r_g)



One time unit = 0.78 years.

Summary

- Luminous AGN are in a very different regime from X-ray binaries in part because they must be very radiation pressure dominated. This makes them very sensitive to opacity effects (talk by Davis).

- Our sub-Eddington accretion simulations are magnetically dominated, which probably provides thermal stability.

- Accretion in AGN0.07 proceeds in the surface layers (cf. Zhu & Stone 2018, Mishra et al. 2019). Dissipation of accretion power is therefore external to the photosphere, leading to almost uniform radiation pressure inside the optically thick portions of the disk.

- Surface densities and effective optical depths DECREASE with decreasing accretion rate, in contrast to standard alpha-disk models. X-ray coronae might therefore form at lower Eddington ratios.

- Further out, iron opacity kicks in. This leads to (supersonic!) convection, enhanced stresses, transient clump formation (radial mass motion!), and vertical pressure support from cycling turbulence→magnetic pressure→radiation pressure. All this happens on short (~thermal) time scales.

- How sensitive are we to our initial conditions? Is all the above generic? Can it be used to start understanding observed behavior?