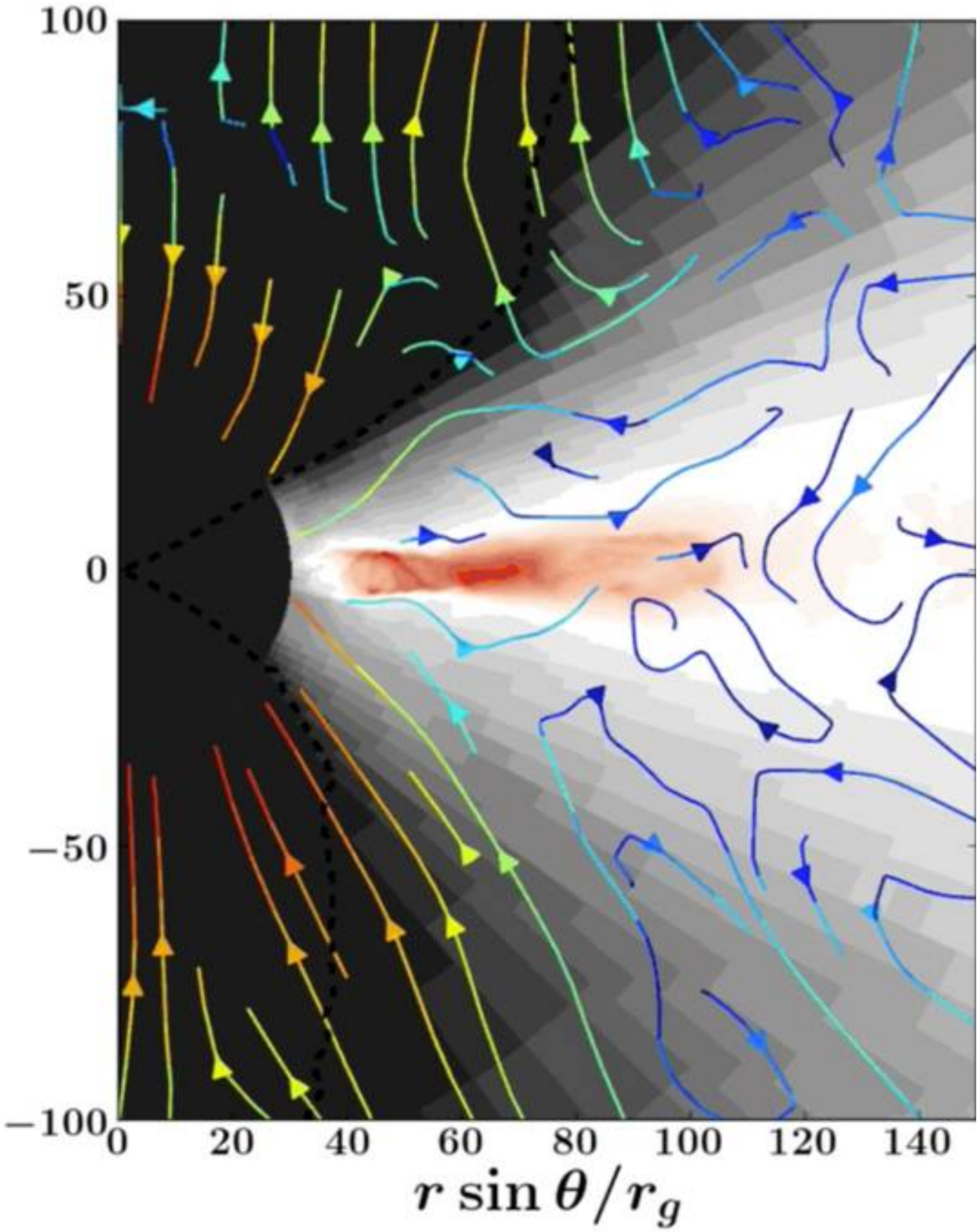
Radiation MHD Simulations of the Structure and Variability of Luminous AGN Accretion Disks

Omer Blaes (UCSB)



Mapping Central Regions
of Active Galactic Nuclei
桂林
September 21, 2019

Collaborators

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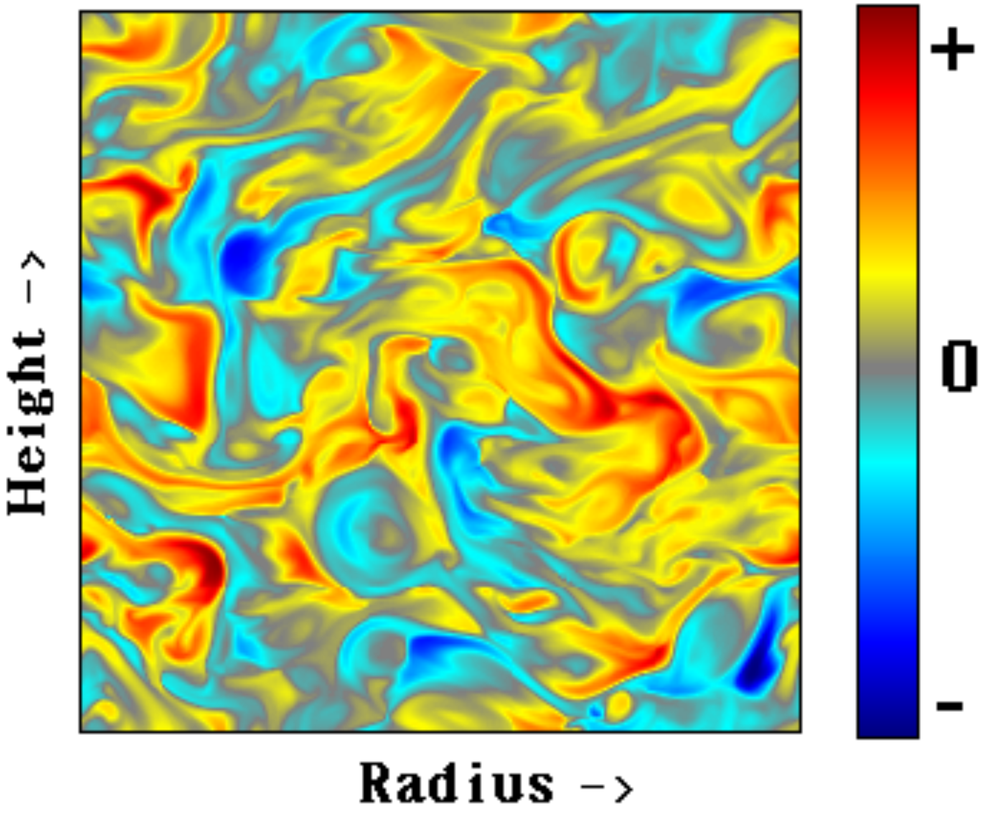
- Yan-Fei Jiang 姜燕飞 (UCSB/KITP)
- Jim Stone (Princeton)

The Accretion Disk Paradigm: MRI Turbulence

- Weak magnetic fields, with local dissipation and transport

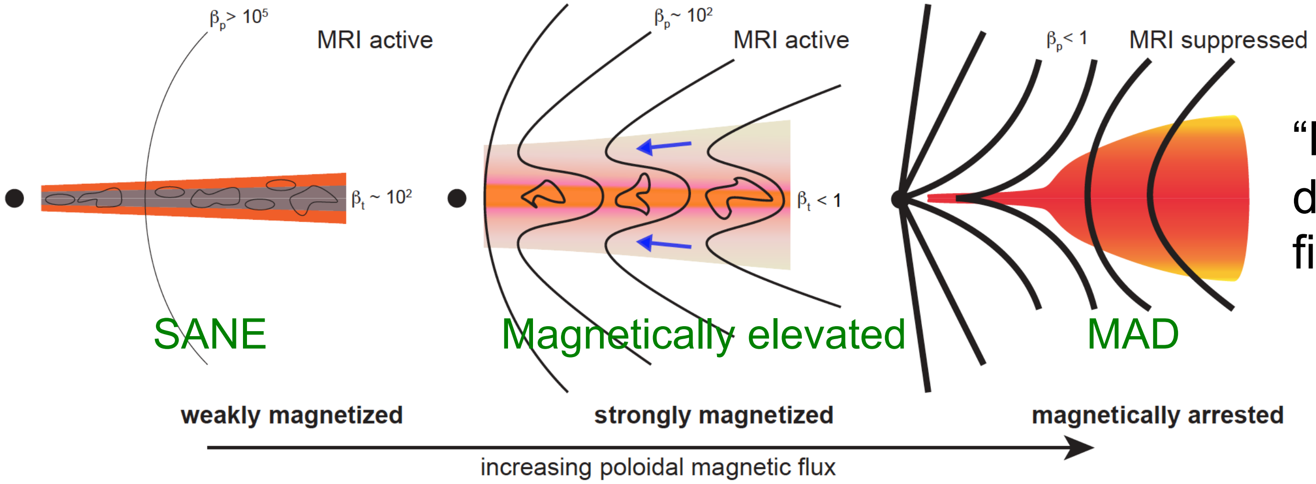


Snapshot of angular momentum per unit mass in MRI turbulence.

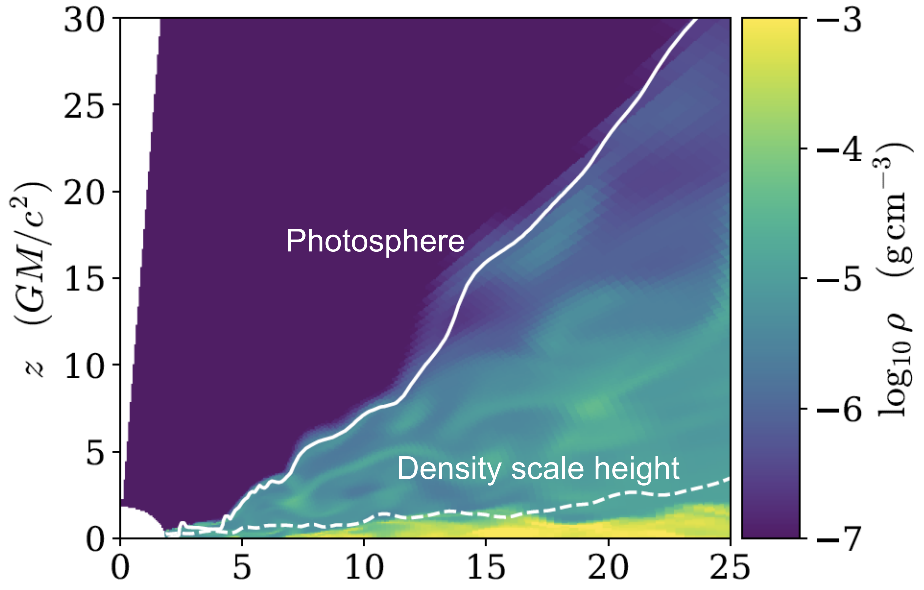
$$\tau_{R\phi} = \overline{\rho} < \mathrm{v}_R \mathrm{v}_\phi - B_R B_\phi /(4\pi\rho) >$$

-Hawley & Balbus (1992)

But magnetic fields matter, and it is NOT just MRI turbulence!

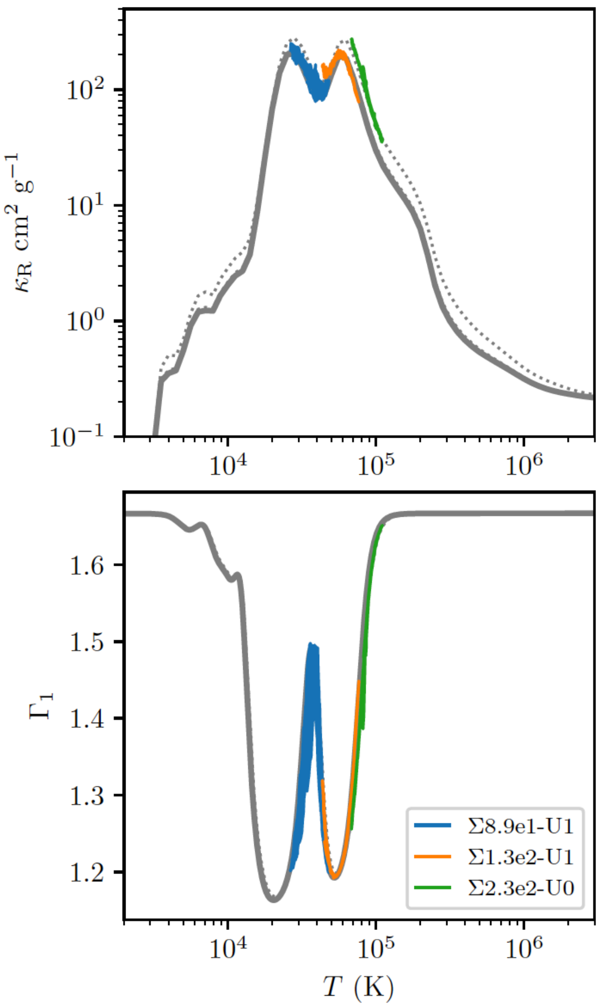


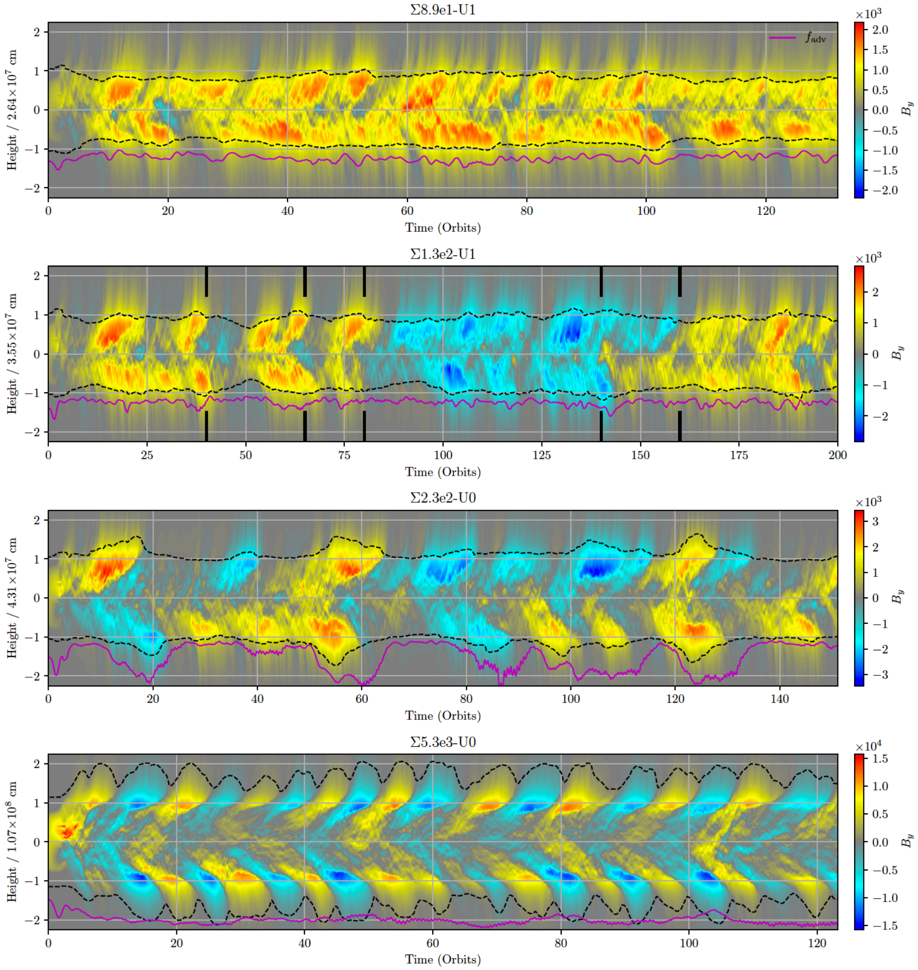
“Magnetically elevated” disks with net vertical field (Mishra et al. 2019)



“Puffy” accretion disks (Lancova et al. 2019) with net radial field in midplane (stellar mass black hole).

Thermodynamics Also Strongly Affects MRI Turbulence





Persistent Convection

Persistent Convection

Intermittent Convection

Radiative

-Vertically stratified shearing box simulations of local patch of AM CVn (helium) disk (Coleman et al. 2018)

The Code: Athena++ (Stone et al. 2008, …)

- Newtonian MHD with a Paczyński-Wiita potential:

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

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

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

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

Gas-radiation exchange terms

$$\phi = -\frac{GM_{\rm BH}}{r - 2r_g}$$

-Jiang, Stone, & Davis (2019)

(GR is on the way, the difficulty being coupling to the radiation.)

- Fully kinetic treatment of photons, with frequency-integrated transfer equation with 80 propagation directions **n**:

$$\frac{\partial I}{\partial t} + c\mathbf{n}.\nabla I = S(I,\mathbf{n})$$

(lab frame)

Absorption opacity momentum exchange

Thomson scattering momentum exchange

$$S(I_0,\mathbf{n}_0) = c\rho\kappa_{aR}\left(\frac{aT^4}{4\pi} - I_0\right) + c\rho\kappa_s(J_0 - I_0)$$

$$+c\rho(\kappa_{aP} - \kappa_{aR})\left(\frac{aT^4}{4\pi} - J_0\right) + c\rho\kappa_s\frac{4k(T - T_r)}{m_e c^2}J_0$$

Absorption opacity energy exchange

Compton scattering energy exchange

(fluid rest frame source terms)

Why Simulate AGN Accretion Disks?!?

Because they are “bat-winged [etc.] unicorns” (Jonathan Trump), i.e. they are cool!

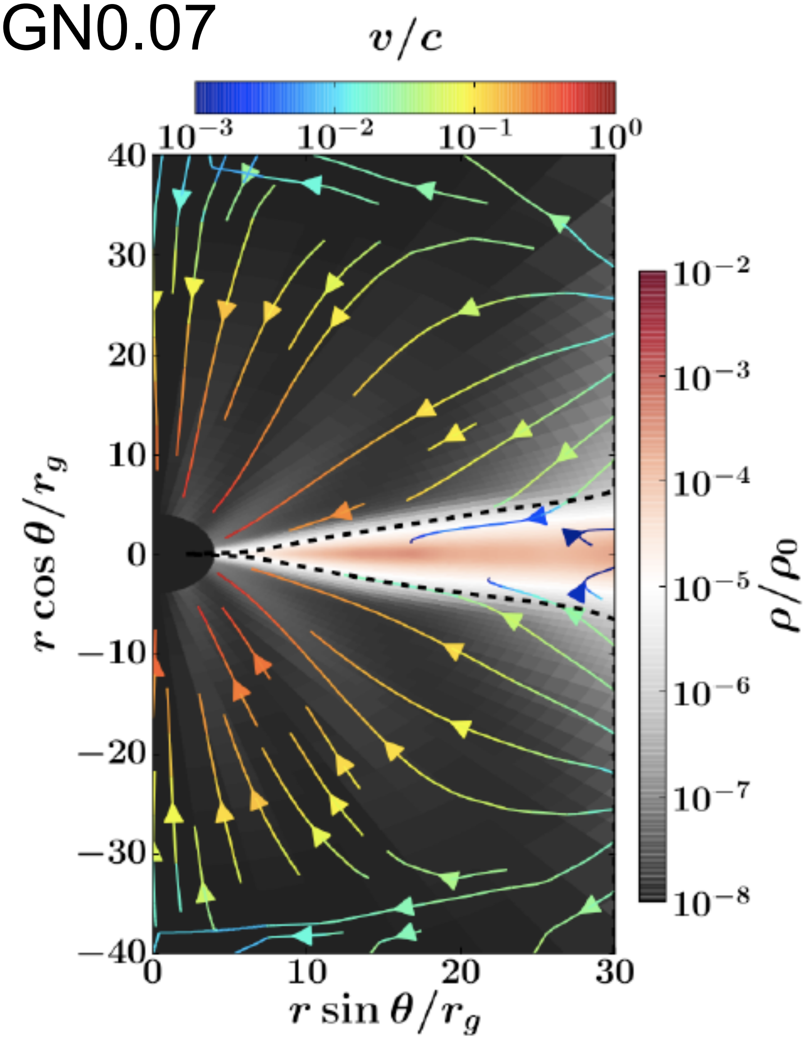
Luminous AGN flows are hugely radiation pressure dominated, with very interesting physics!

(Some) Physics Issues Associated with Radiation Pressure

- Thermal Instability
- Radiation Viscosity and Bulk Comptonization
  (Loeb & Laor 1992, Kaufman & Blaes 2016)
- Very high sensitivity to opacities
- Outflows
  (Proga, Stone, & Kallman 2000;
  Takeuchi, Ohsuga, & Mineshige 2013;
  Laor & Davis 2014)

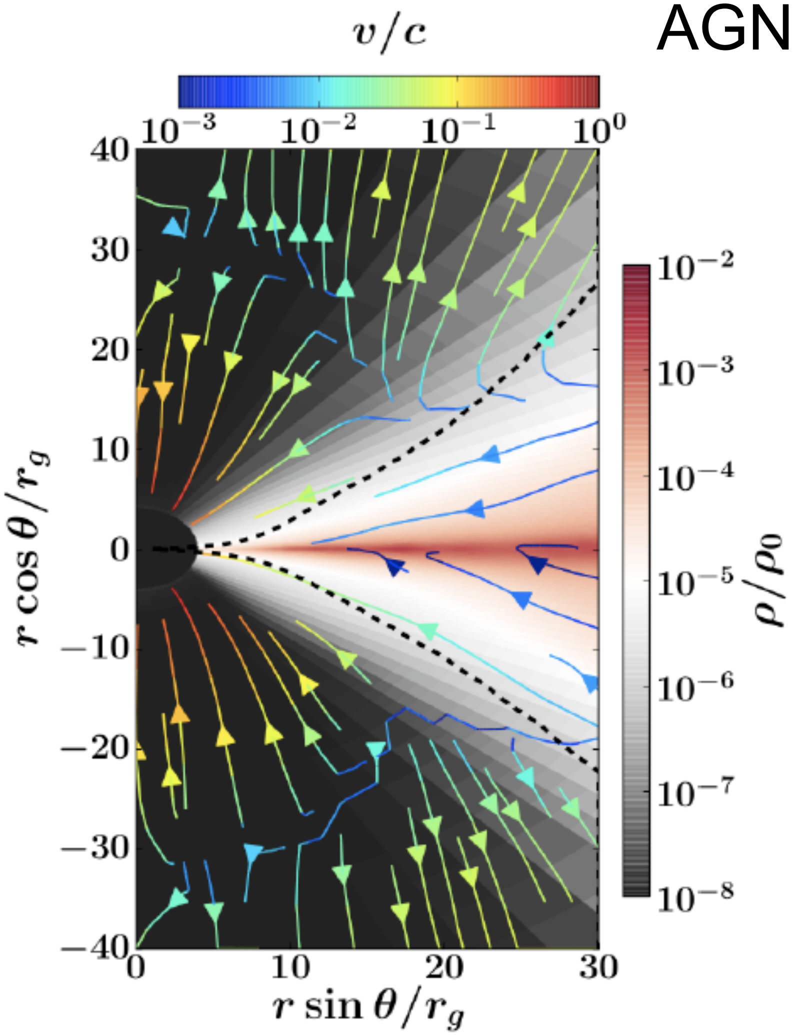
Radiation MHD Simulations of Sub-Eddington Accretion Onto a 5×10^8 Solar Mass Black Hole

AGN0.07



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

AGN0.2

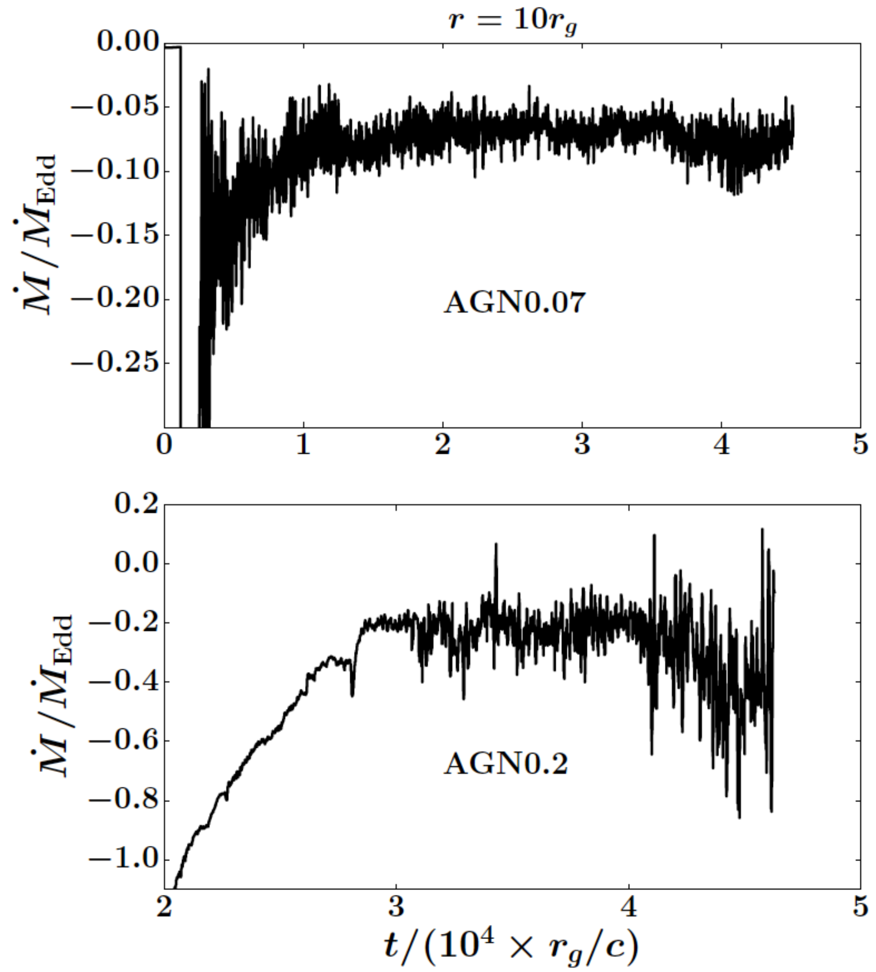


Initialized with stronger, single poloidal loop

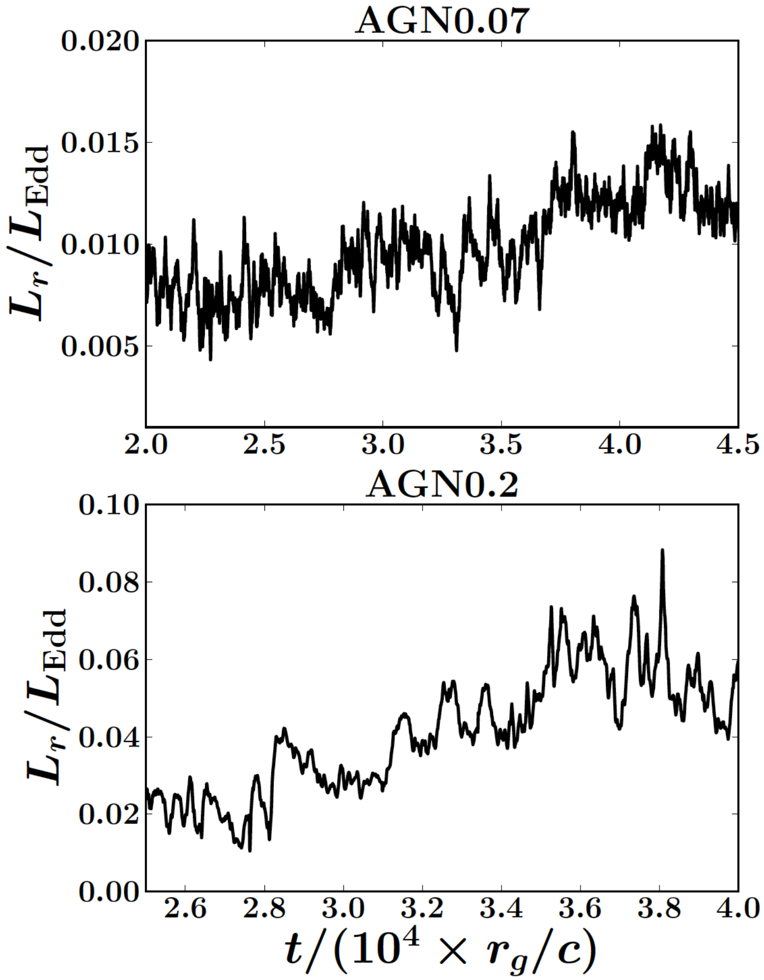
-Jiang, Blaes, Stone, & Davis (2019)

NO Radiation Pressure Driven Thermal Instability, Because These Disks Turn Out to be Magnetically Supported (Sadowski 2016)

Accretion rate at 10 r_g

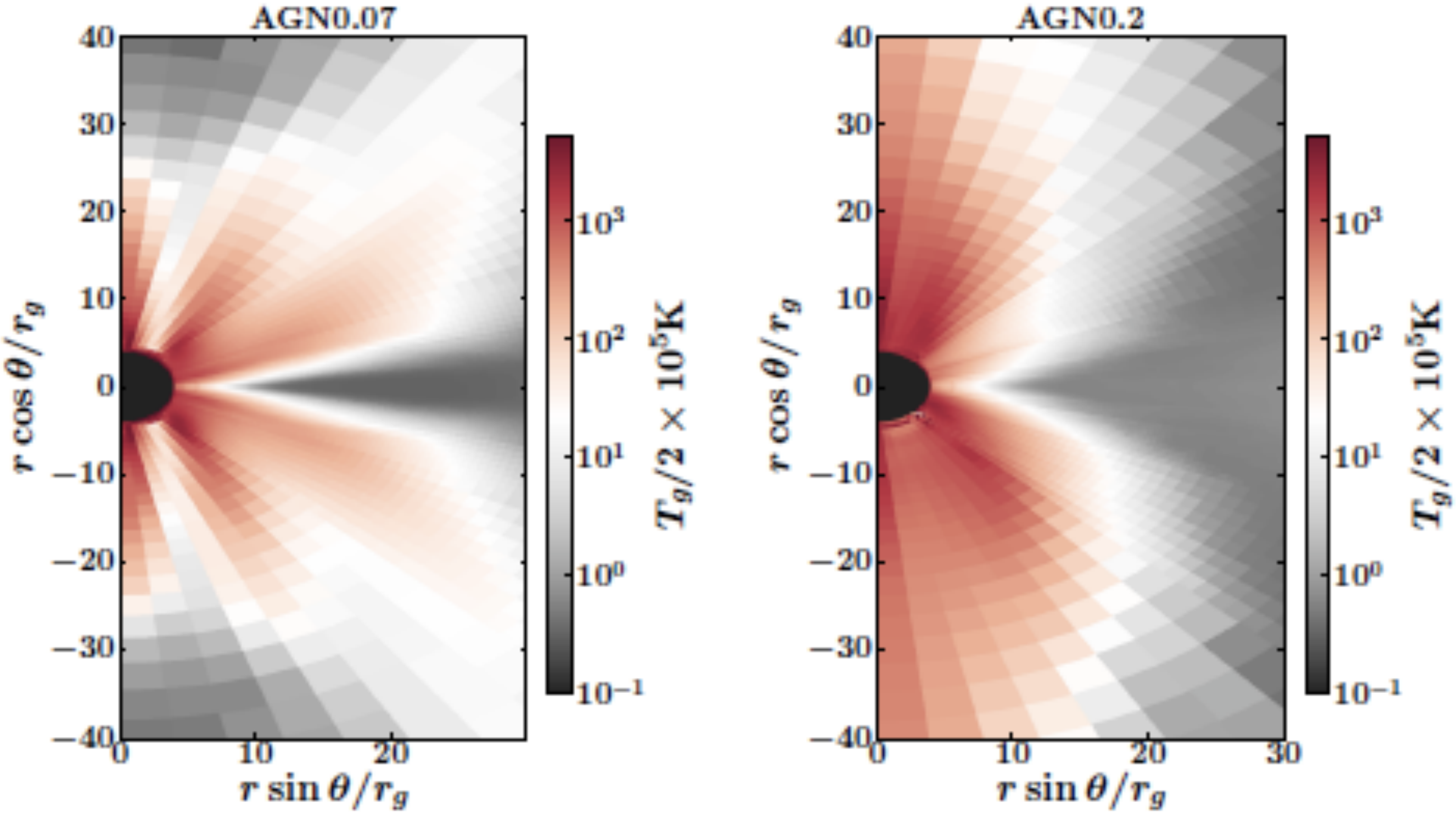


Total luminosity



Time unit = 0.78 years

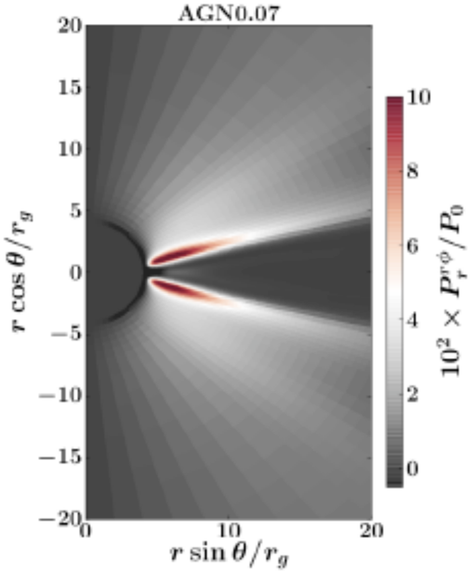
A Compact Hot “Corona” is Present



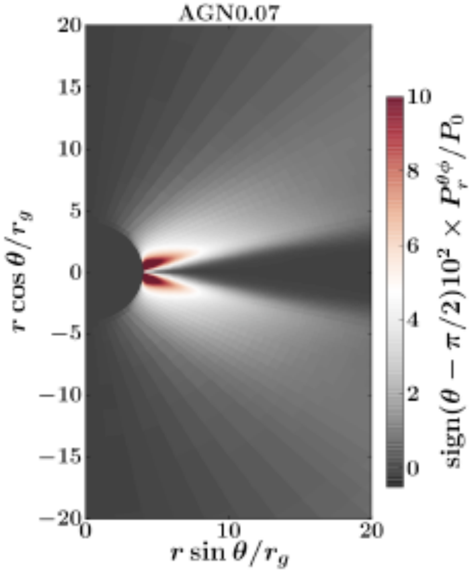
-AGN0.07 (lower Eddington ratio) has LOWER effective optical depth than AGN0.2. Caveat – we only have two simulations.

Most of the accretion happens ABOVE the photosphere in AGN0.07 in a surface accretion flow.

Angular momentum transport in these layers occurs by bulk Comptonization of photons traversing the shear.

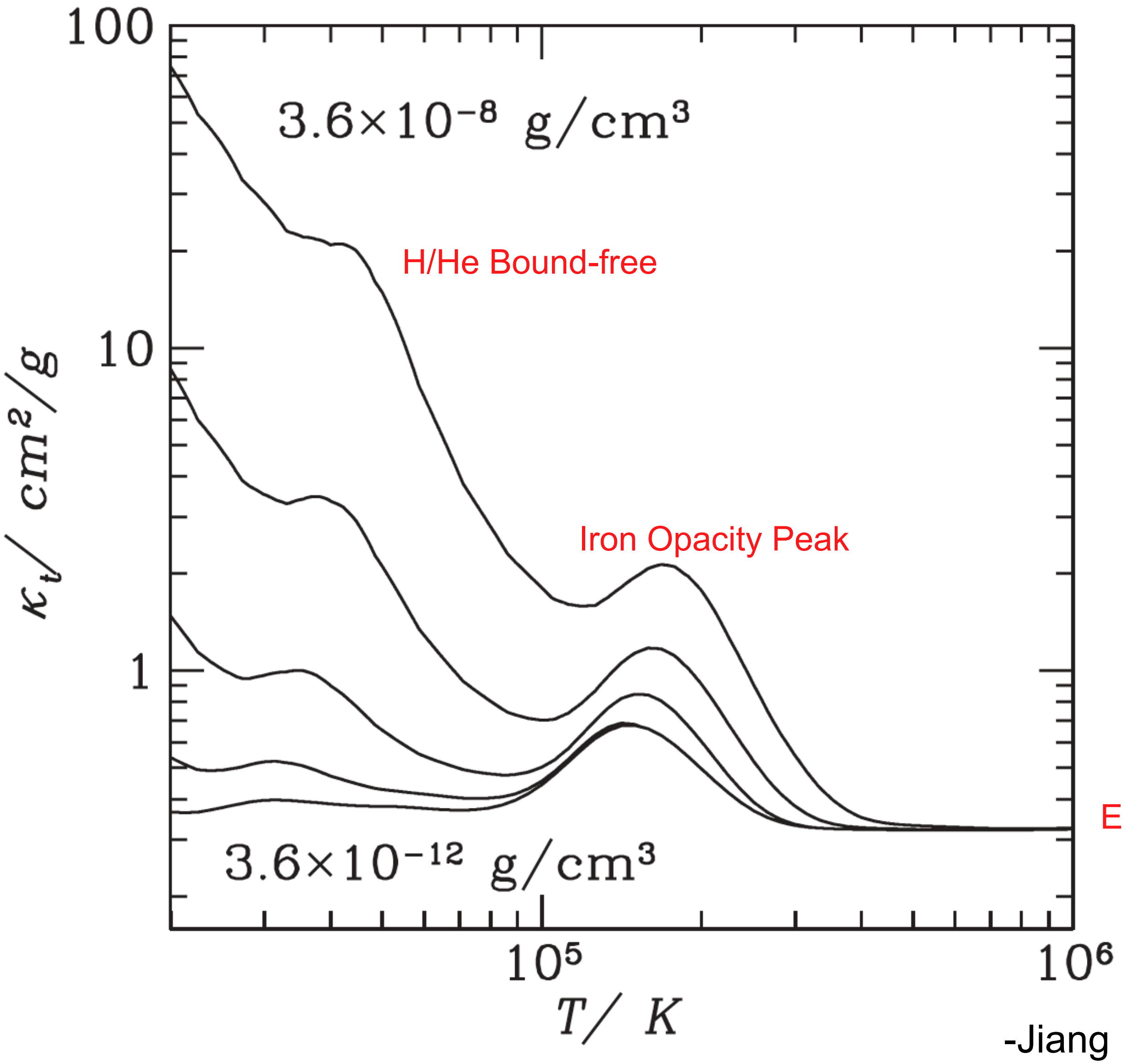


Radiation (rφ)



Radiation (θφ)

Rosseland Opacity under Massive Star (or AGN) Conditions



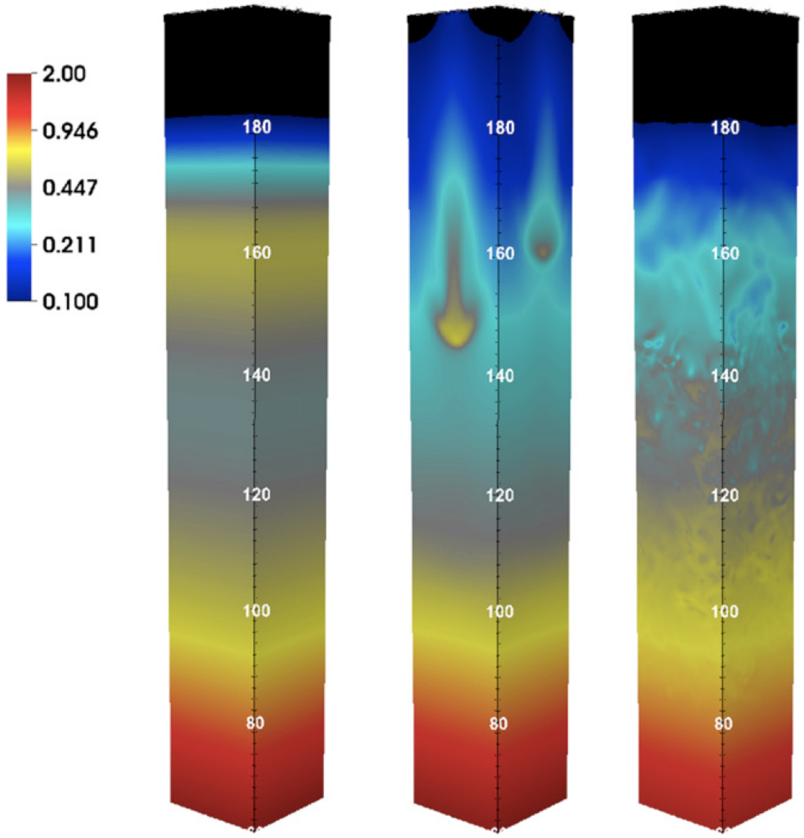
H/He Bound-free

Iron Opacity Peak

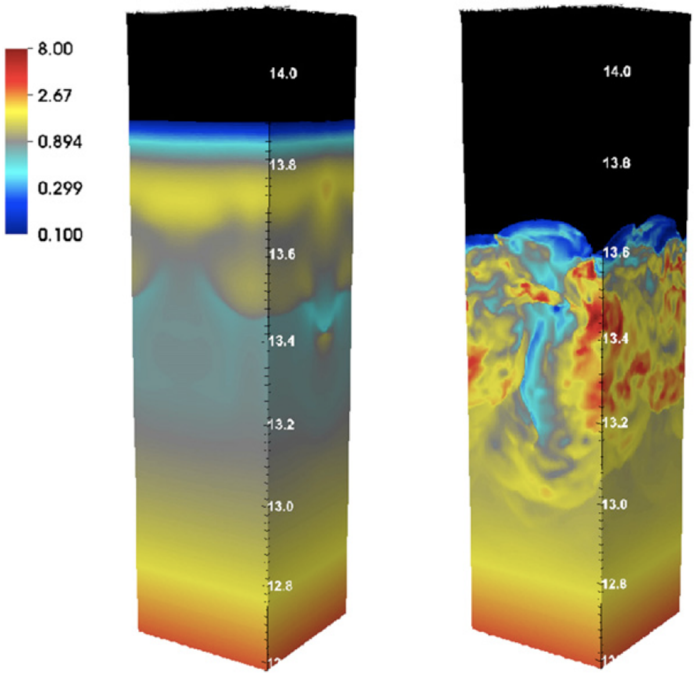
Electron Scattering

-Jiang et al. (2015)

Iron Opacity Effects in Massive Stars



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



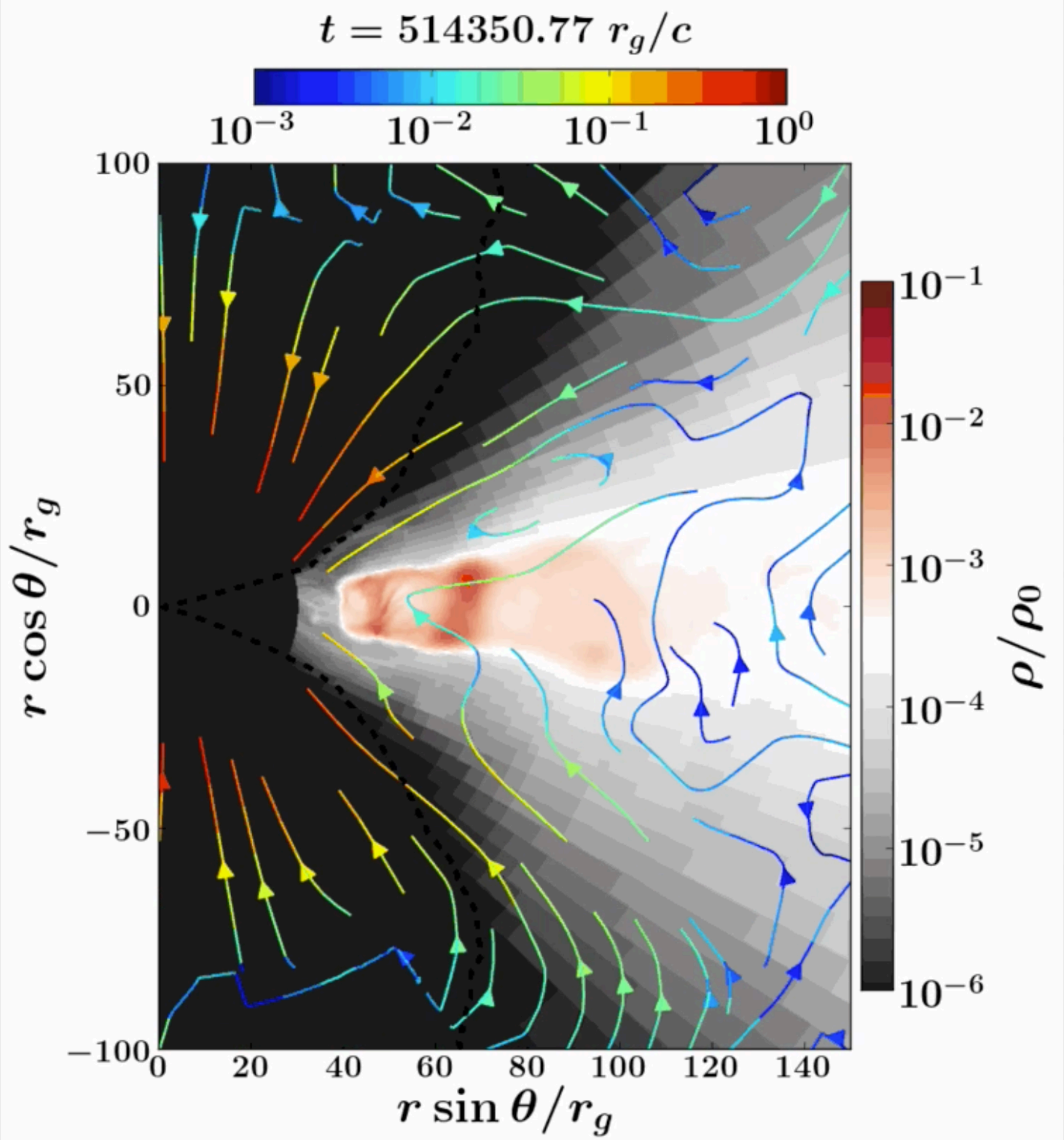
Rapid photon diffusion:
strong turbulence results in
porous medium. Density inversion is
maintained in time/space average.

-Jiang et al. (2015)

In disks, convection can enhance MRI angular momentum transport (Hirose et al. 2014, Scepi et al. 2018).

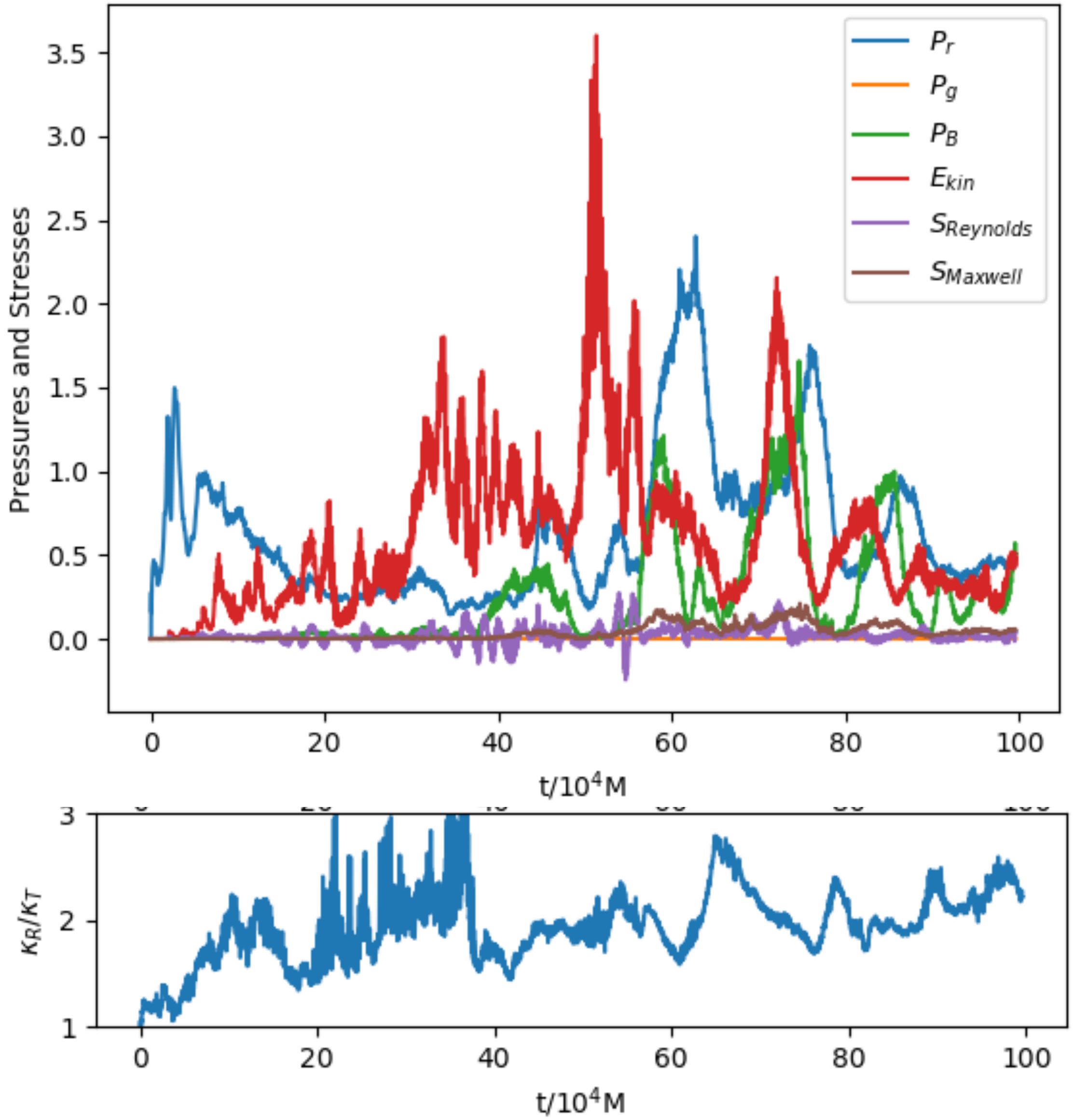
OK – so what happens when we combine radiation pressure with the iron opacity peak in an AGN disk?

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

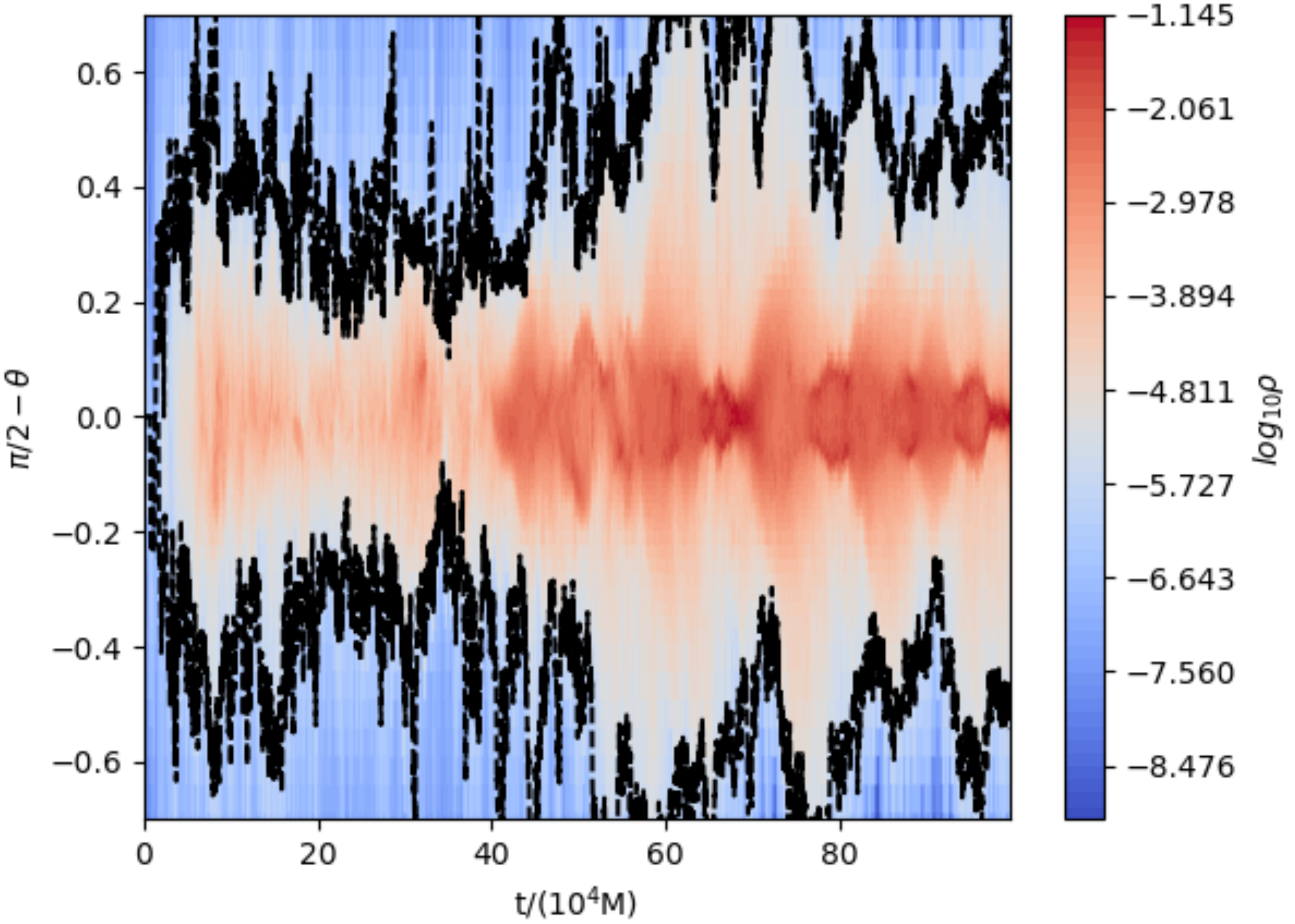


$t = 514350.77\ r_g/c$
10^{-3}
10^{-2}
10^{-1}
10^{0}
100
50
0
−50
−100
0
20
40
60
80
100
120
140
$r\cos\theta/r_g$
$r\sin\theta/r_g$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ρ/ρ_0

Variability of Various Pressures and Energy Densities at 47 r_g

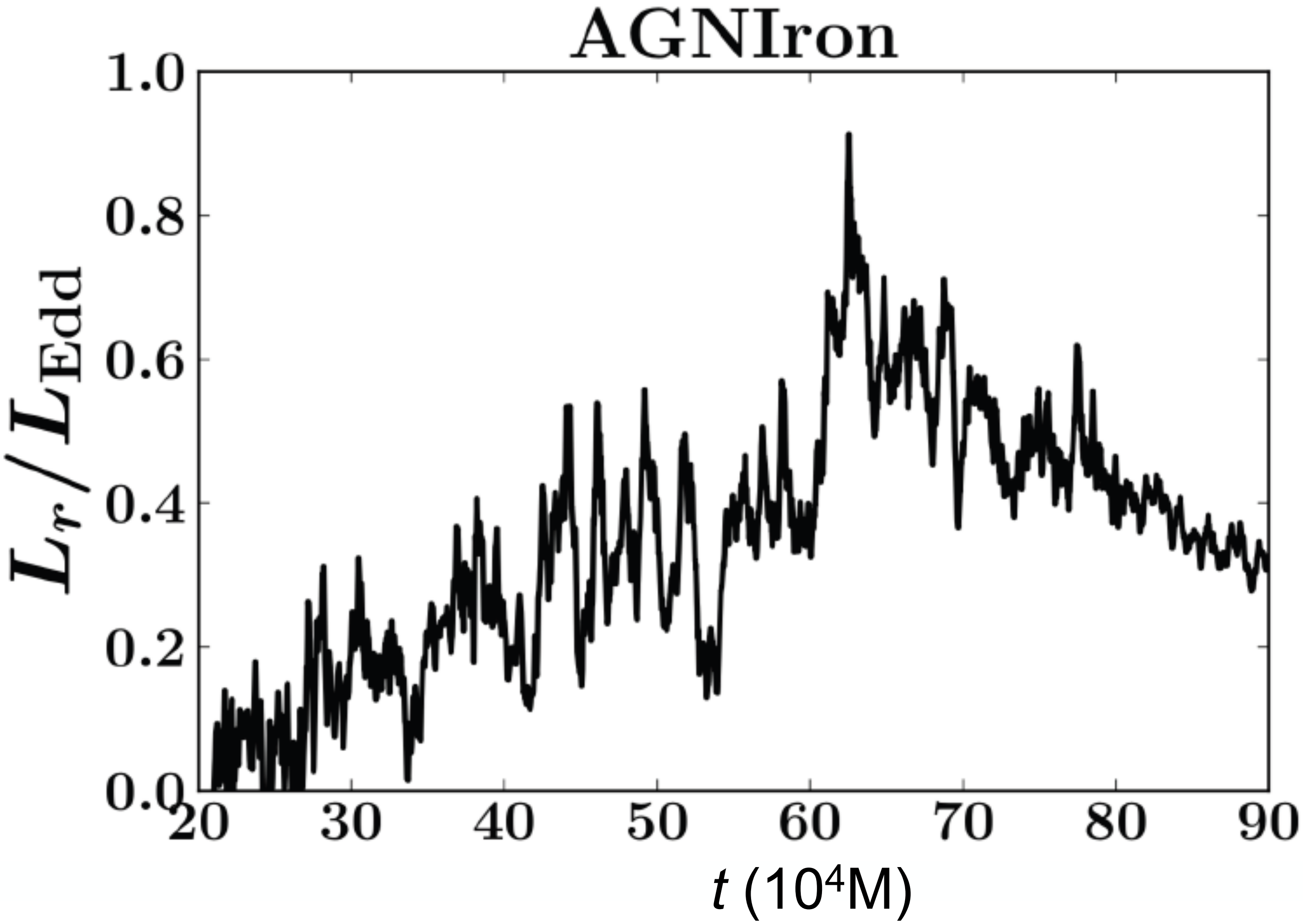


Disk is quite thick, with substantial variations in height of photosphere.



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 other accretion disk systems in part because of the enormous radiation pressure which is very sensitive to UV opacities.

- Our sub-Eddington inner accretion disk 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) and is aided by radiation bulk viscosity. Dissipation of accretion power is external to the photosphere. How might this affect the disk spectrum (e.g. bound-free edges)?

- Surface densities and effective optical depths DECREASE with decreasing accretion rate in the two inner disk simulations, in contrast to standard alpha-disk models. X-ray corona is stronger at the lower Eddington ratio (but we only have the two simulations to compare).

- 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. (CLQs???)

- How sensitive are we to our initial conditions? Is all the above generic? Is there any way to get a handle observationally on the magnetic field topology on the larger scales that feed the AGN inner disk?