Theoretical Issues in Luminous AGN Accretion Flows

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Disks, Dynamos and Data:
Confronting MHD Accretion Theory
with Observations

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Why Discuss AGN?

- Event Horizon Telescope: Sgr A* and M87 (talks on Friday)

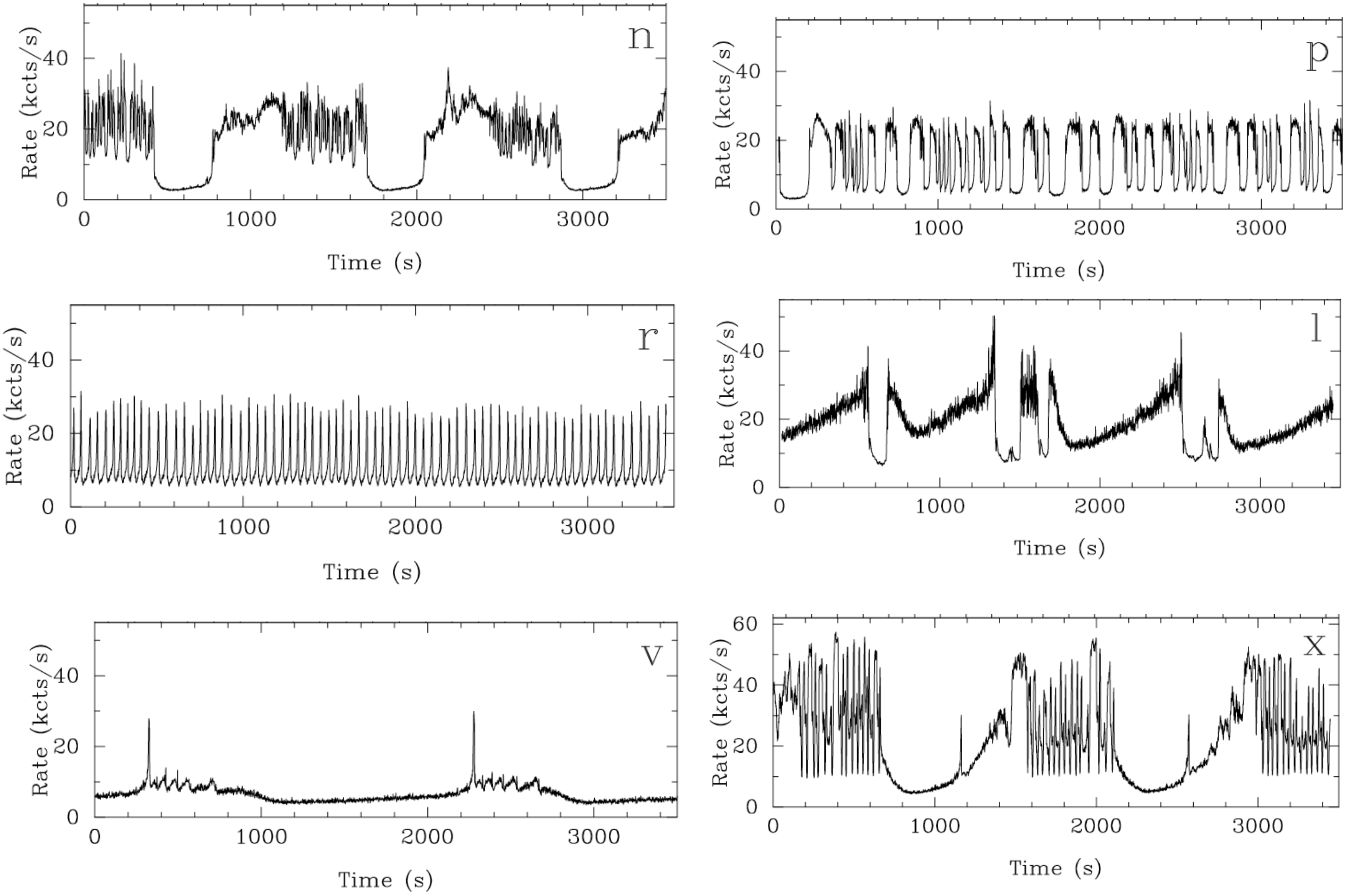
- Well-resolved jet physics, and interesting physics connections between blazars and GRB’s (Tchekhovskoy’s talk)

- Feedback!!! (Sadowski’s talk)

But for accretion physics itself, other source classes have **far** richer data sets and **much** tighter observational constraints.

It is not even clear that we have a good base model for the accretion flow geometry in AGN (Antonucci 2013, 2015).

GRS 1915+105, a Black Hole X-ray Binary



- Belloni et al. (2000)

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

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)

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

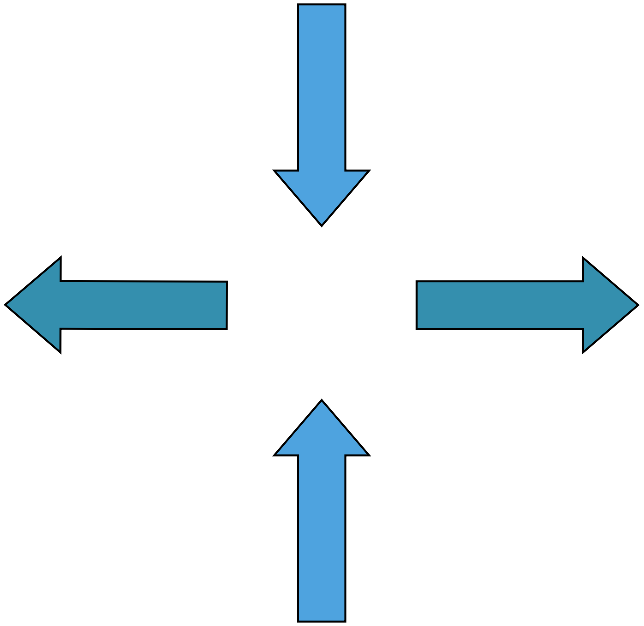
Cf. standard thin disk theory:

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

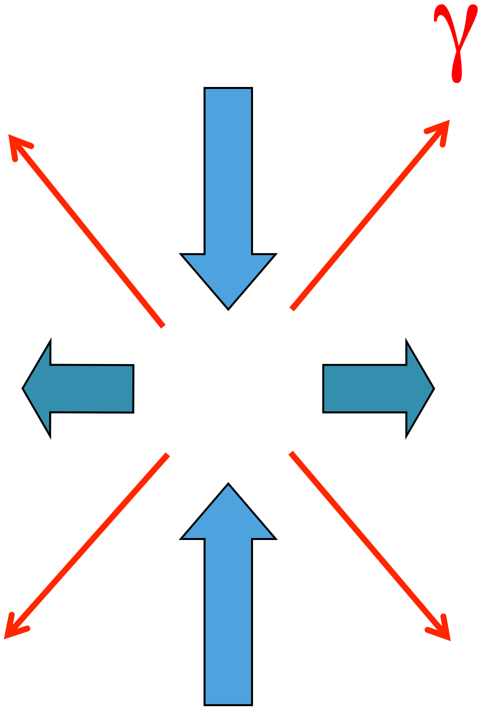
(Some) Physics Issues Associated with Radiation Pressure

- Compressibility and Radiative Damping
- Radiation Pressure Support Constrains Radiative Cooling
- Radiation Advection
- Thermal Stability
- Outflows
- Turbulent Comptonization

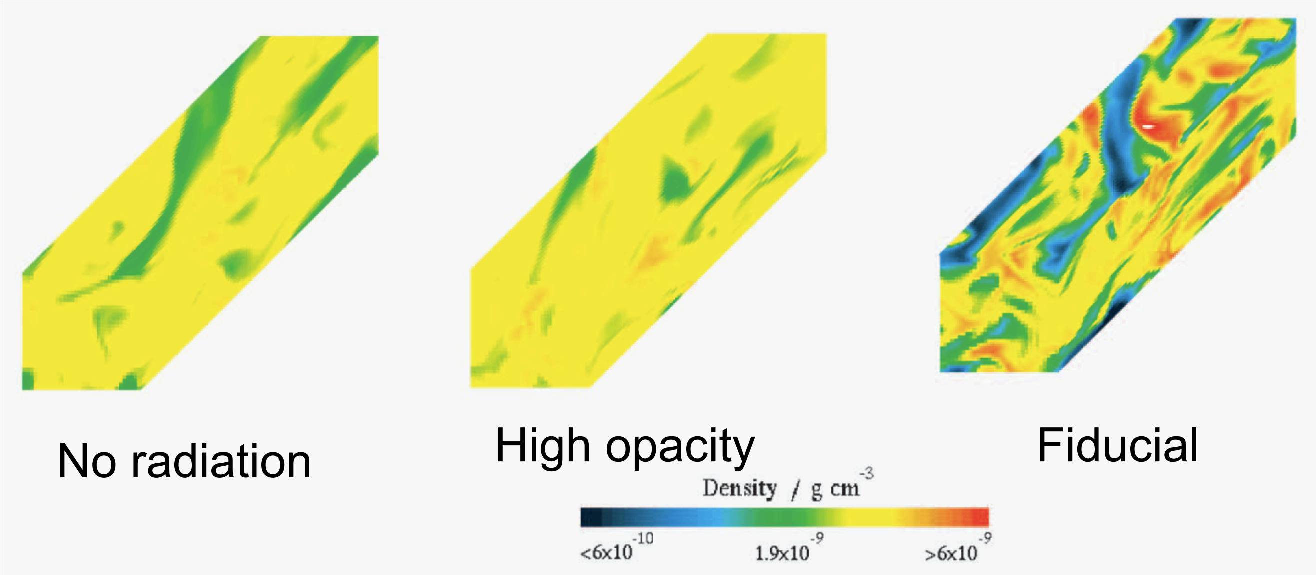
Radiation Pressure Dominated Plasmas are Highly Compressible



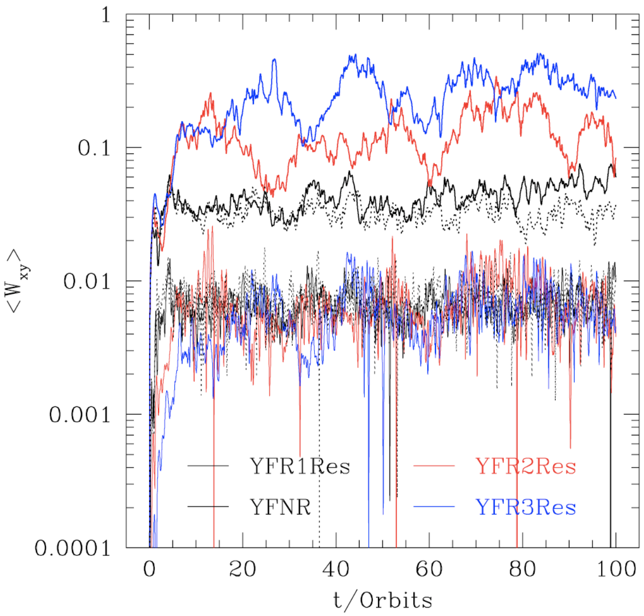
Subsonic motions are usually incompressible.



Motions that are subsonic with respect to the radiation sound speed, but supersonic with respect to the much smaller gas sound speed, can be very compressible.



-Turner et al. (2003)

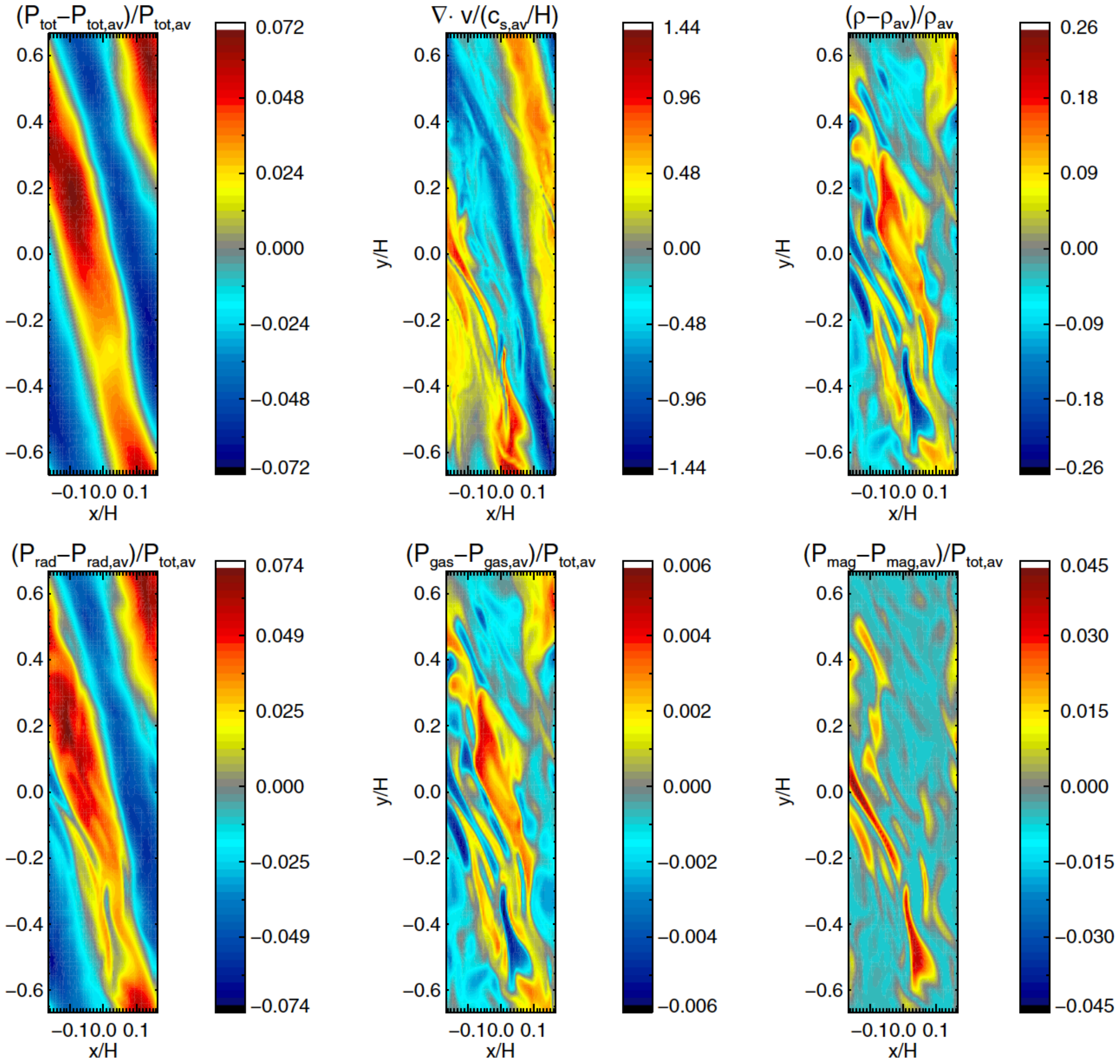


Maxwell stress

Reynolds stress

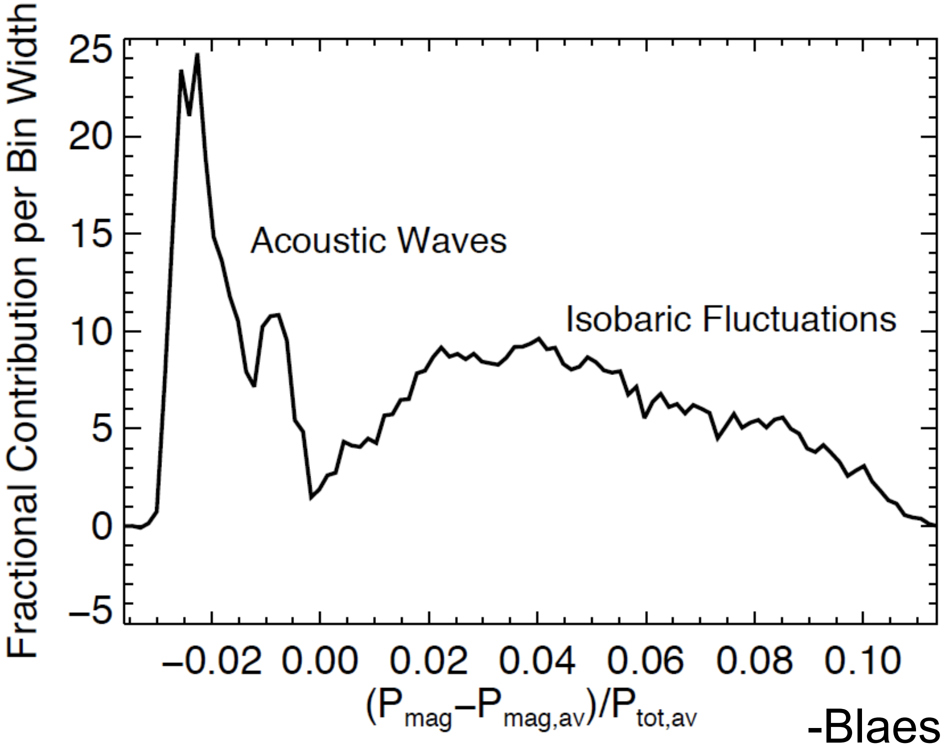
-Jiang, Stone, & Davis (2013)

Radiation-Pressure Dominated MRI Turbulence Exhibits Acoustic Spiral Waves as well as Slow, Isobaric Fluctuations, With Significant Baroclinicity



-Blaes et al. (2011)

Both types of fluctuation are radiatively damped (Agol & Krolik 1998), and this accounts for tens of percent of the total dissipation – and this is numerically RESOLVED!



-Blaes et al. (2011)

Radiative damping of acoustic fluctuations can also account for 10% of total dissipation rate in gas pressure dominated FU Ori simulations (Hirose 2015).

Dynamical and Thermal Equilibrium in a Radiation Pressure Dominated Disk

Hydrostatic equilibrium: $$\frac{\kappa F}{c} = g = \Omega^2 z$$

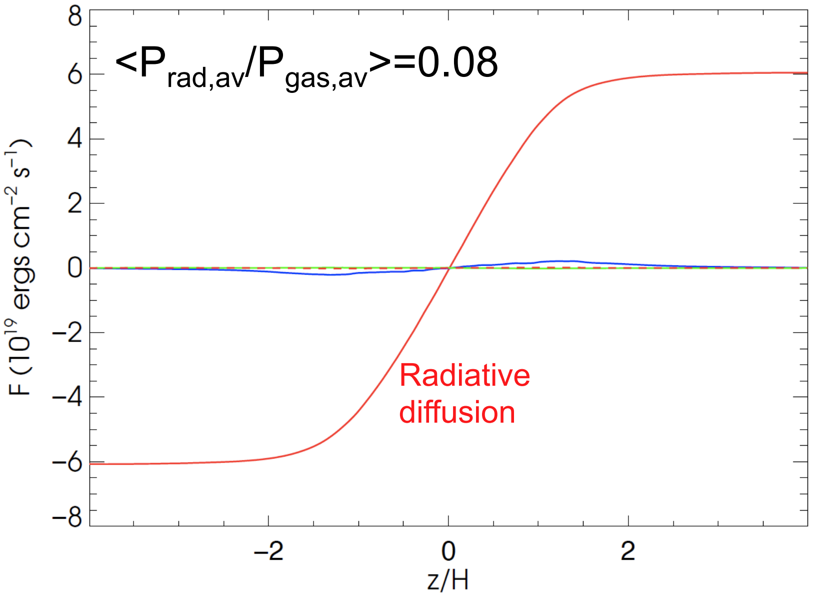
Radiative equilibrium: $$Q = \frac{dF}{dz}$$

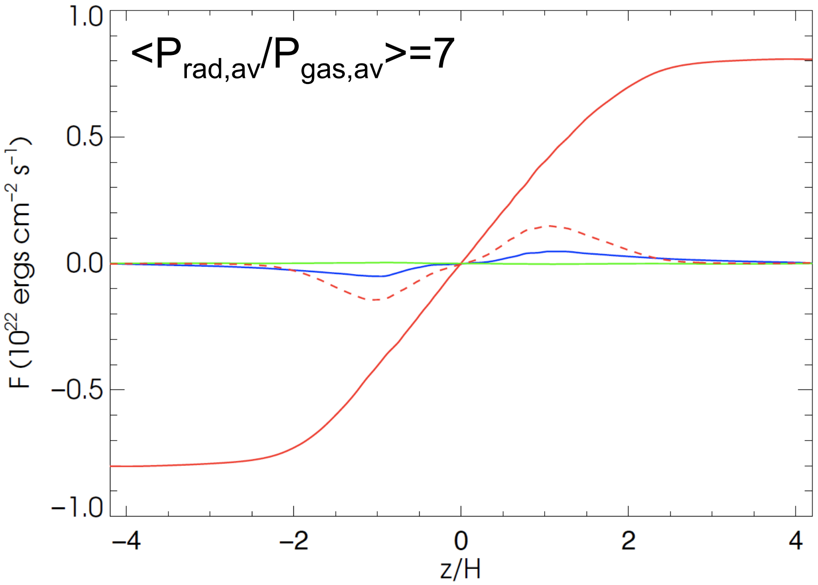
→ A vertically constant dissipation rate per unit volume: $$\boxed{Q = \frac{c\Omega^2}{\kappa}}$$

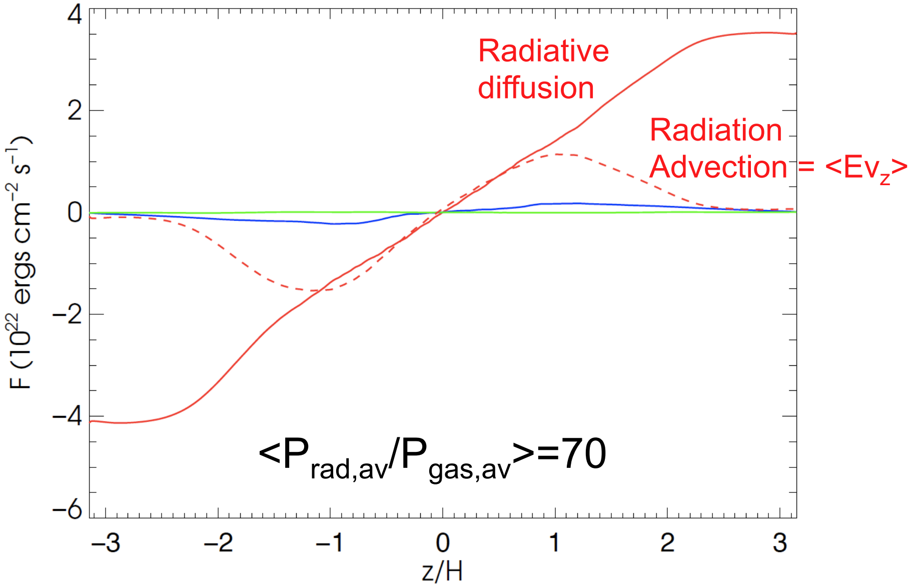
But $$Q \approx \tau_{r\phi}\left(-r\frac{d\Omega}{dr}\right)$$

→ $$\boxed{\tau_{r\phi} \approx \frac{2c\Omega}{3\kappa}}$$ (Shakura & Sunyaev 1976)

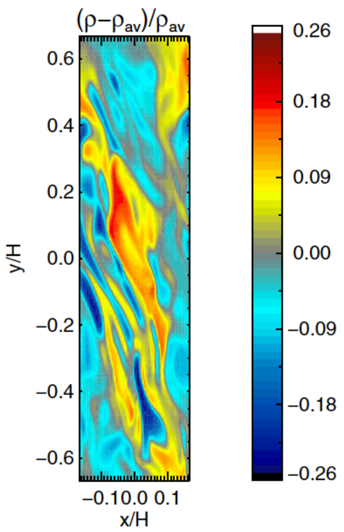
But MRI Turbulence Does Not Obey this Dissipation Constraint And Radiative Equilibrium is Broken

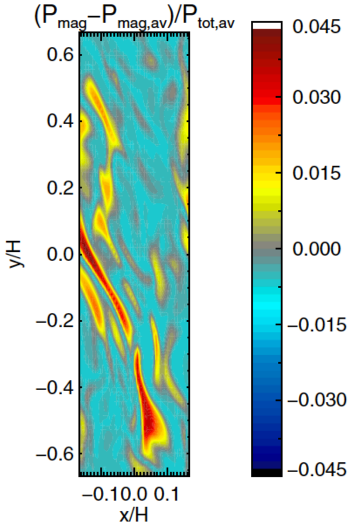


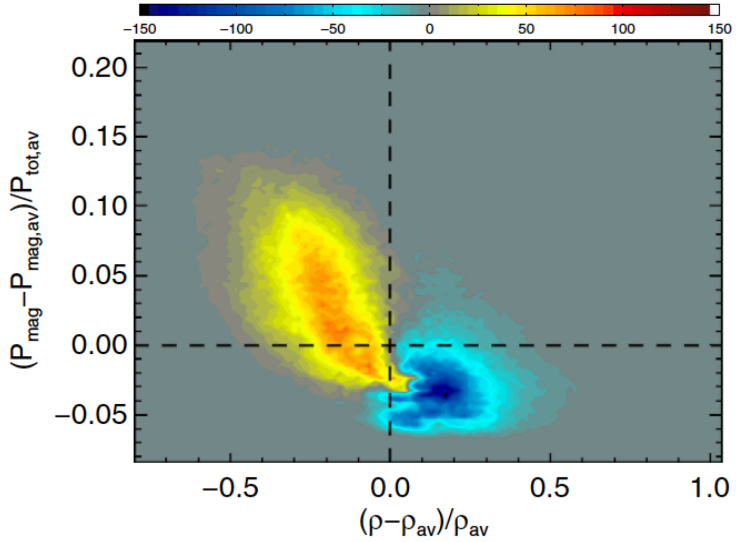




Radiation Advection (NOT Convection!) is Due to Buoyant, Localized Concentrations of Magnetic Field

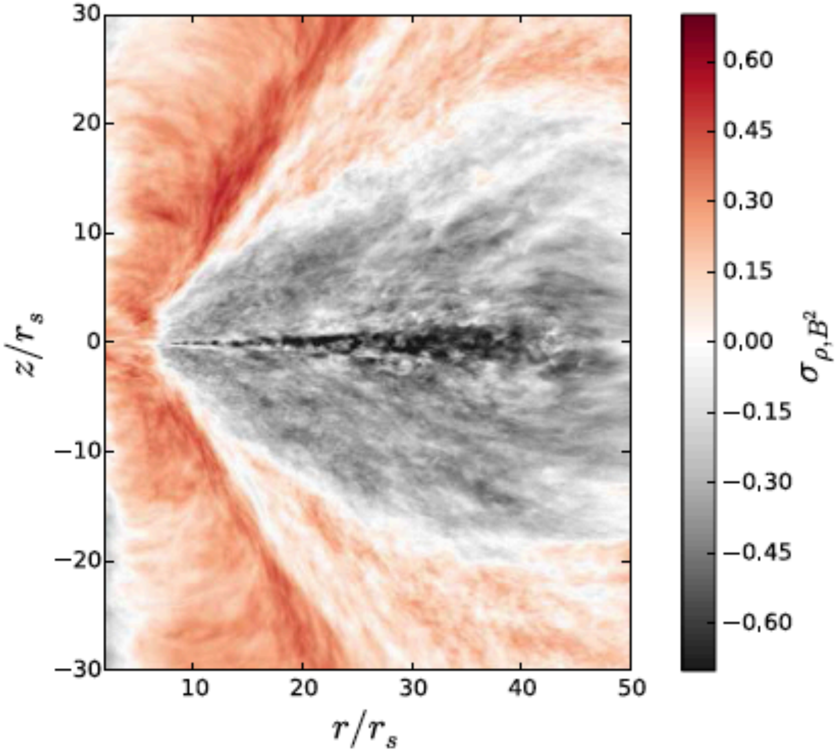




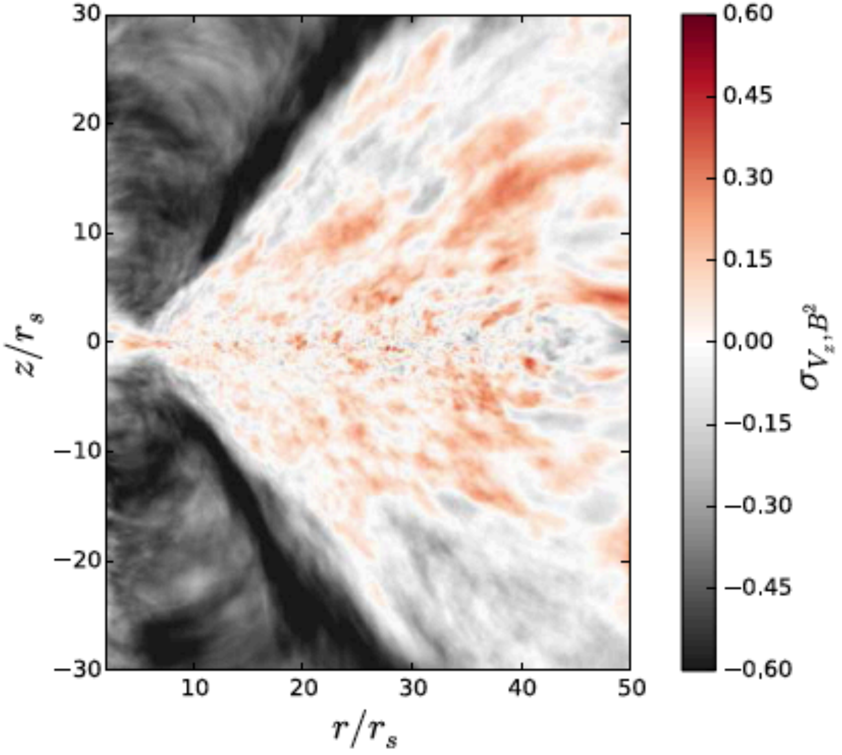


-Blaes et al. (2011)

Vertical Radiation Advection Also Observed in (some) Global Simulations



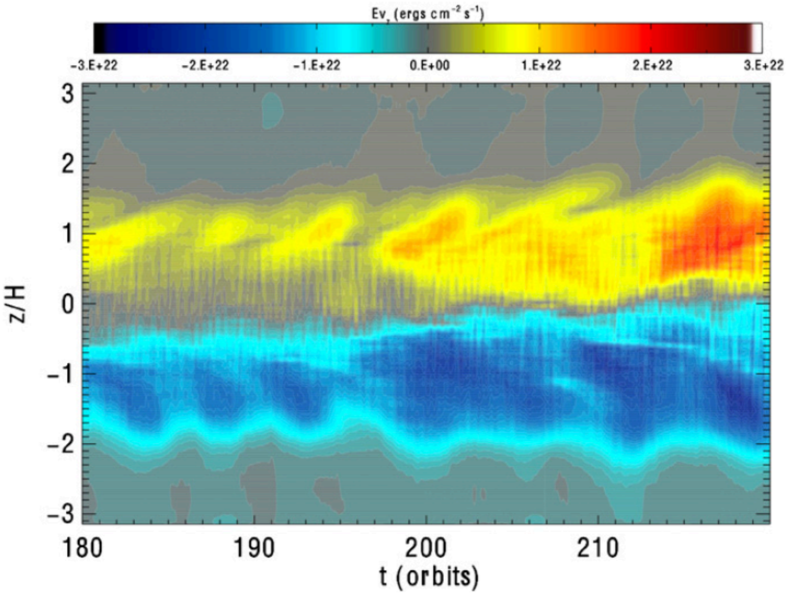
Density & magnetic pressure are anti-correlated.

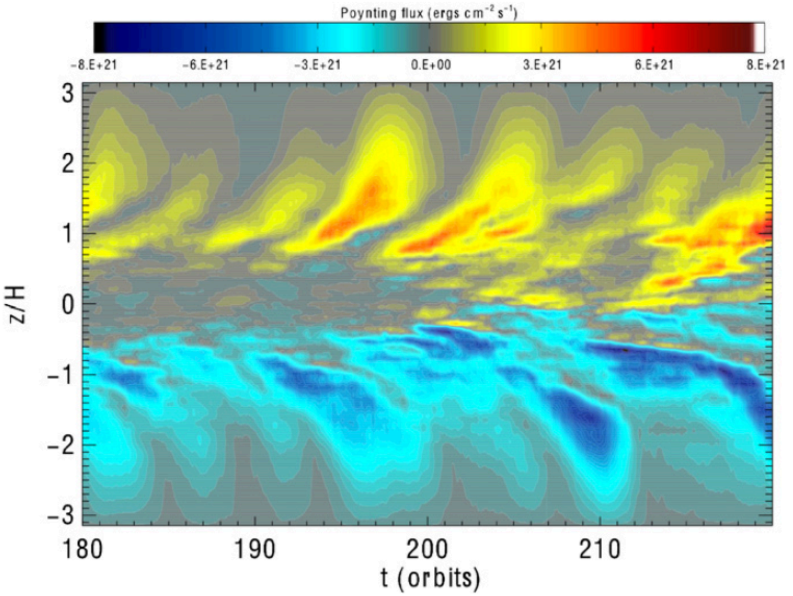


Vertical velocity & magnetic pressure are correlated.

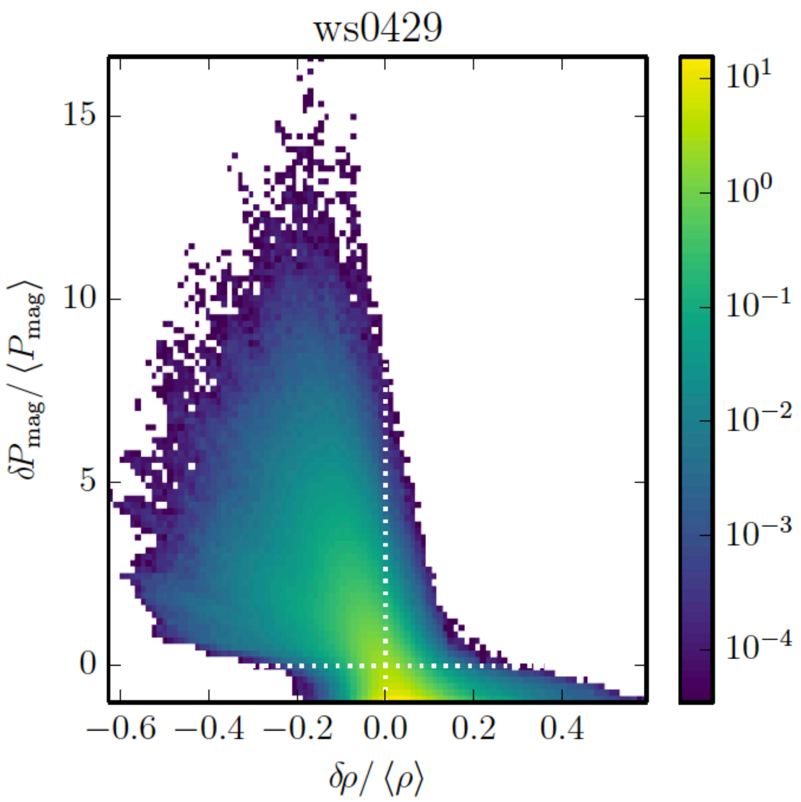
-Jiang, Stone & Davis (2014)

Buoyant Magnetic Concentrations are an Essential Component of the MRI Butterfly Dynamo





-Blaes et al. (2011)



Dwarf nova stratified shearing box simulation (Hirose et al. 2014, Coleman et al. 2017) – no convection in this case but still outward Poynting flux due to magnetic buoyancy.

Thermal Instability

$$\text{Cooling} \approx \frac{4caT^4}{3\kappa\Sigma} \propto \frac{T^4}{\kappa\Sigma}$$

If $\tau_{r\phi} = \alpha P_{\rm tot}$, then in the radiation pressure dominated regime,

$$\text{Heating} \approx 2H\tau_{r\phi} r\left|\frac{d\Omega}{dr}\right| \propto \frac{T^8}{\Sigma}$$

➡ Runaway heating or cooling (Shakura & Sunyaev 1976)

“Viscous” instability is also predicted (Lightman & Eardley 1974), but can’t be tested in shearing box simulations.

Thermal Instability

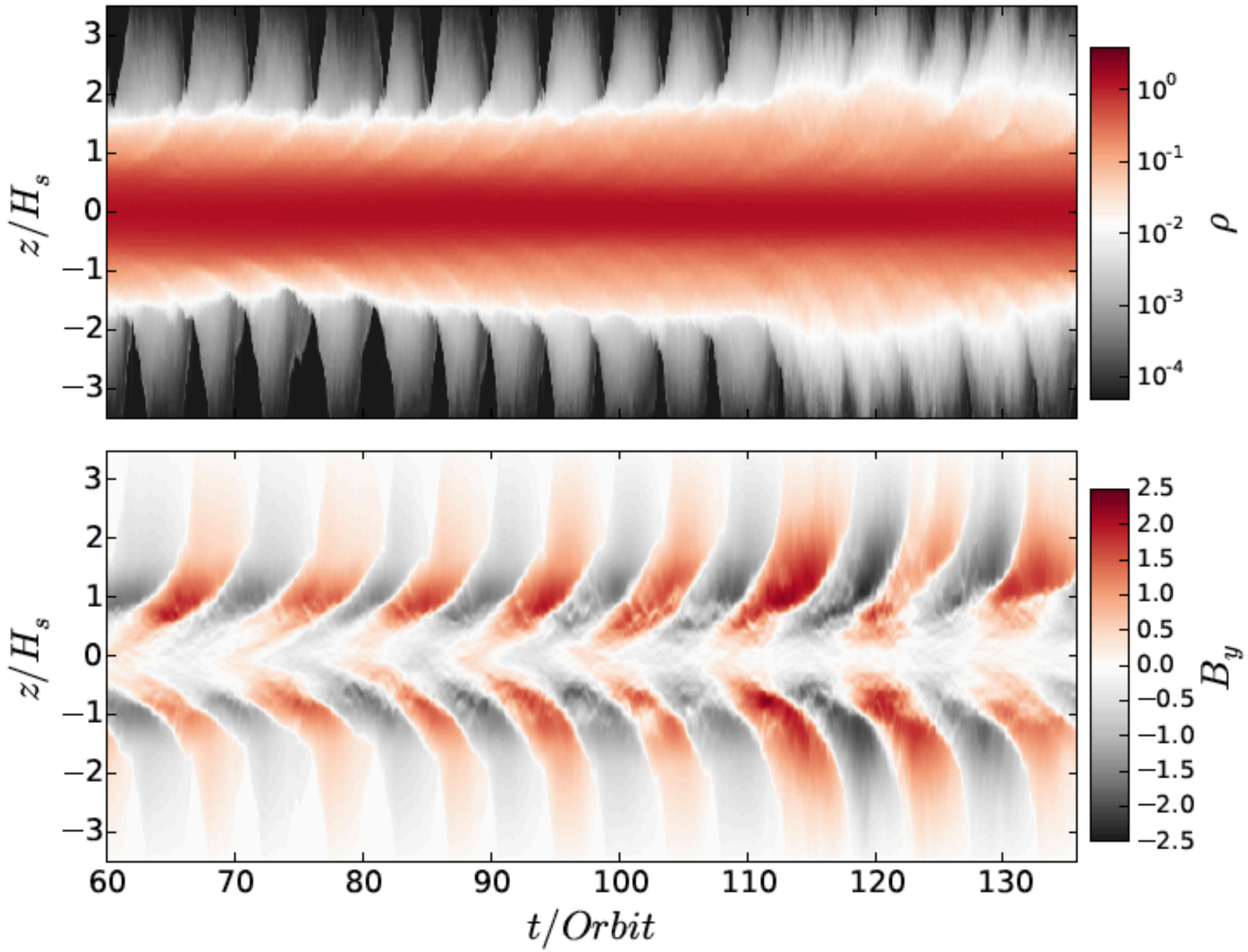
Much work on this using stratified shearing boxes, with mixed results:
Turner (2004); Hirose et al. (2009); Jiang, Stone & Davis (2013)

It appears that thermal instability is genuine, BUT

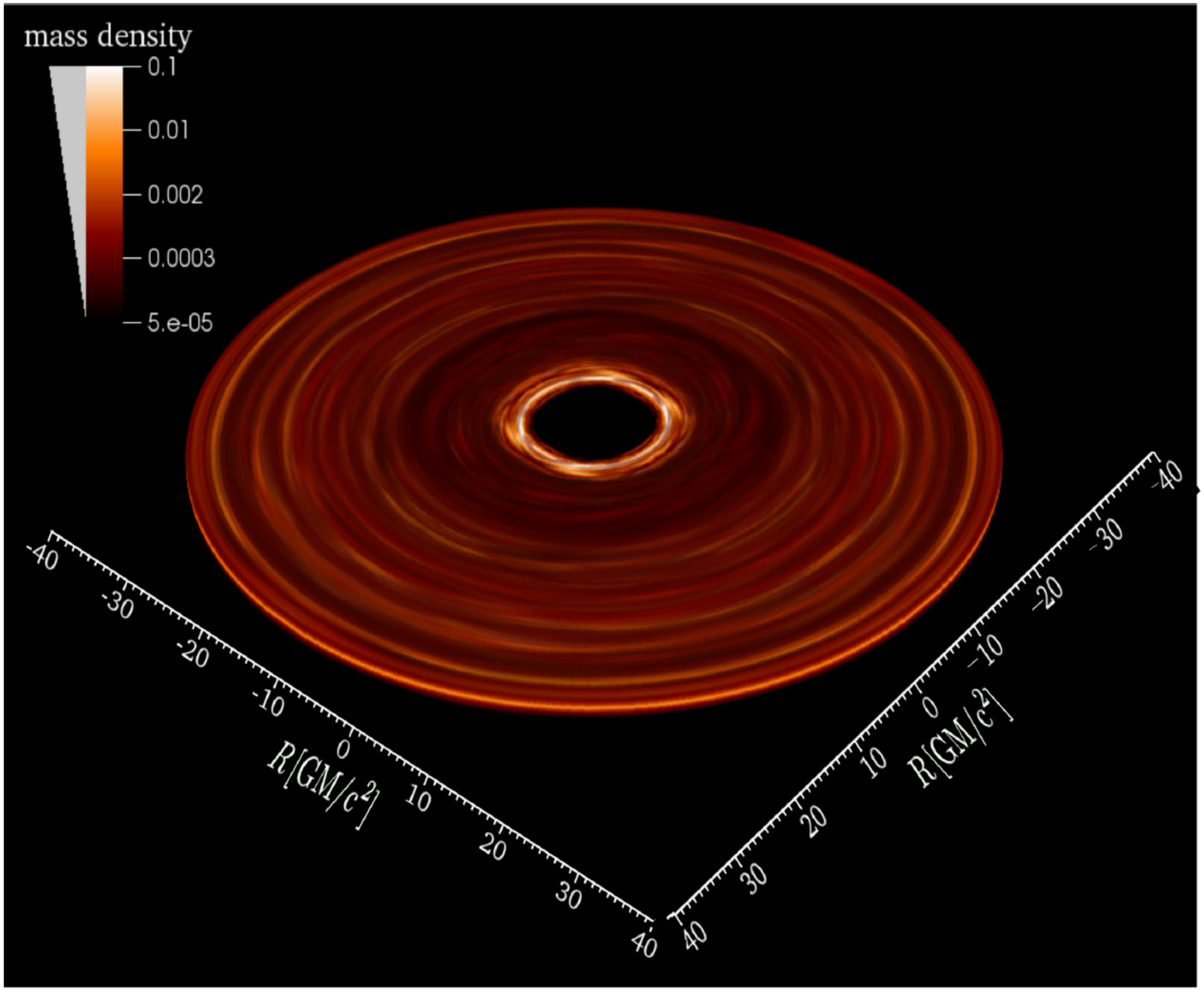
Iron opacity bump can stabilize certain radial ranges of AGN accretion disks (Jiang, Davis & Stone 2016) by giving an optical depth that declines with temperature and by enhancing radiation advection.

Strongly magnetically pressure supported disks can be stabilized, as heating rate is then determined by magnetic rather than thermal pressure (Sadowski 2016). How magnetized are AGN disks?

What about slim disks?

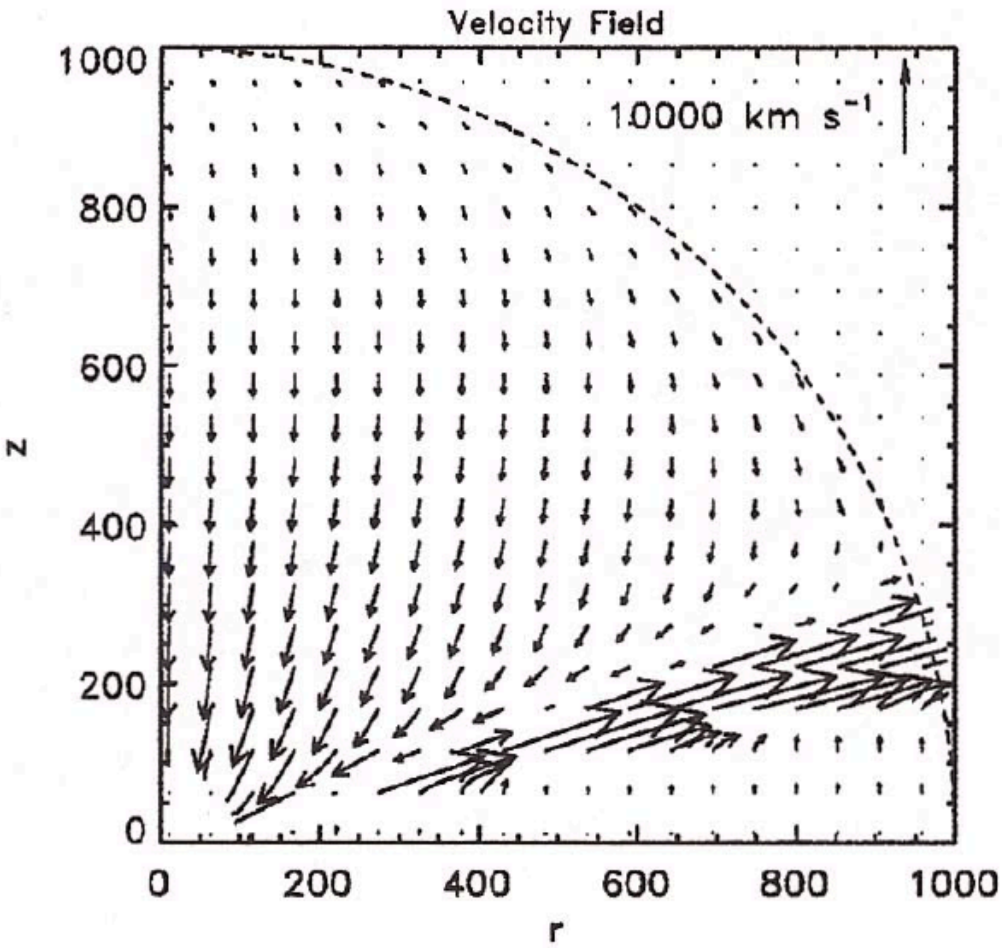


-Jiang, Davis, & Stone (2016)



-Hints of Lightman-Eardley viscous instability (Mishra et al. 2017)?

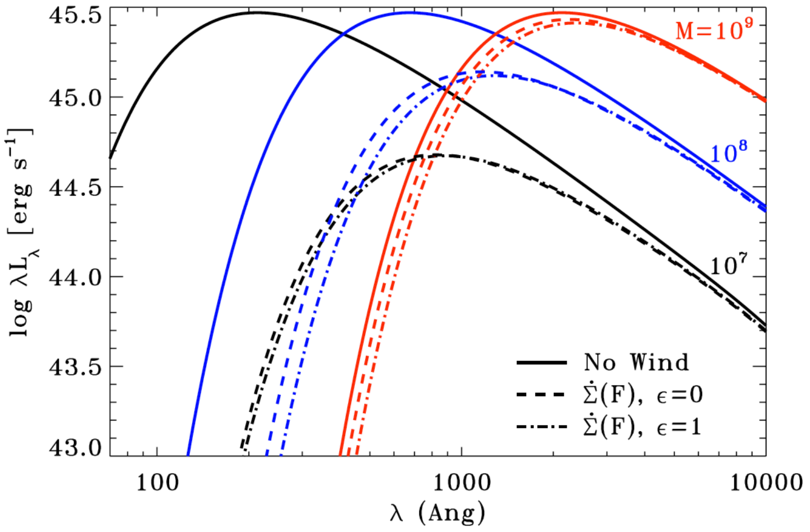
Outflows



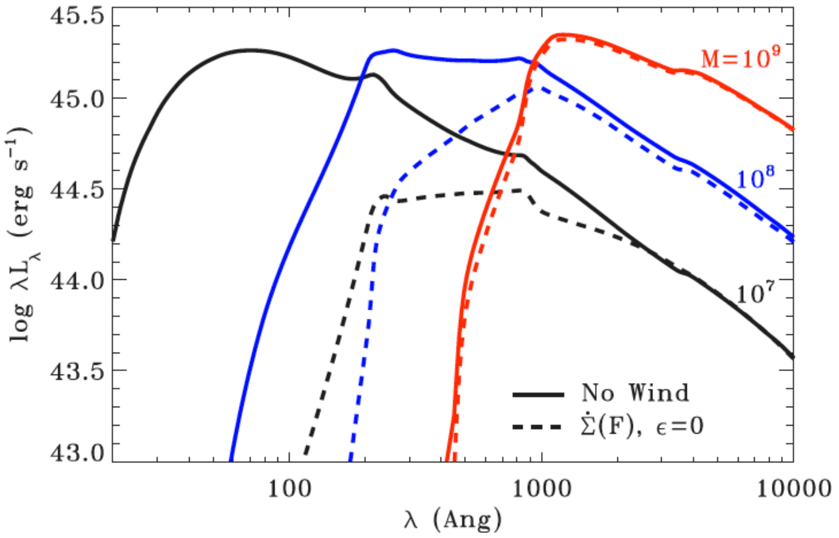
-Proga, Stone & Kallman (2000)

See talks by Higginbottom & Proga.

Simple Models Based on Stellar Winds



Local Blackbody Models



Non-LTE Atmosphere Models

$$\log \dot{\Sigma} = 1.9 \log F / \mathrm{F}_\odot - 15.7$$

-Laor & Davis (2014)

-Outflows may be key to understanding the large microlensing and reverberation sizes, both because Mdot is not constant and because of back-scattering illuminating the outer disk.

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

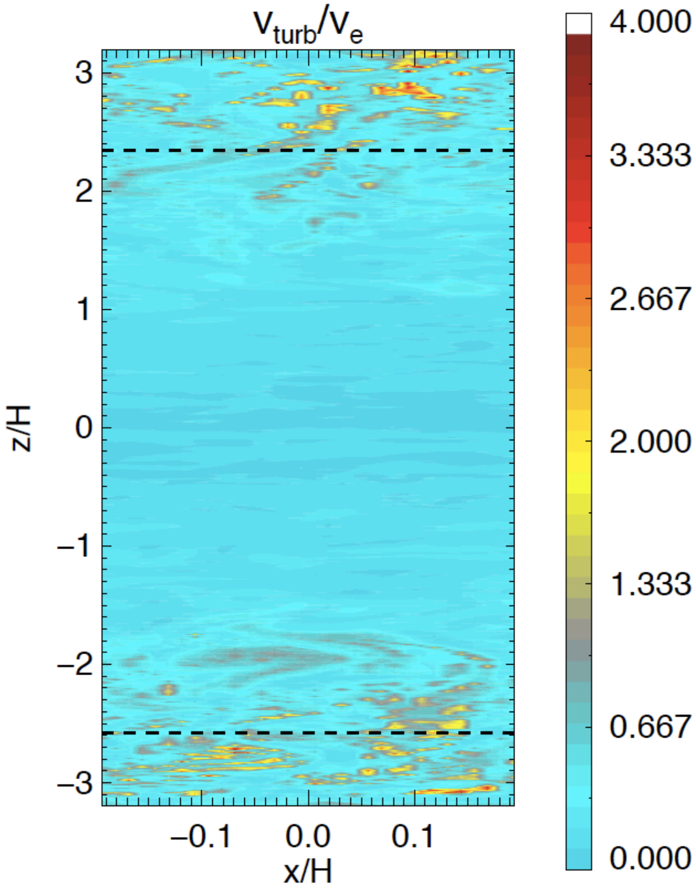
$$< v_e^2 >^{1/2} = \left(\frac{3kT}{m_\mathrm{e}}\right)^{1/2} \sim \left(\frac{P_\mathrm{gas}}{\rho}\right)^{1/2} \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^{1/2} \sim c_\mathrm{gas} \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^{1/2}$$

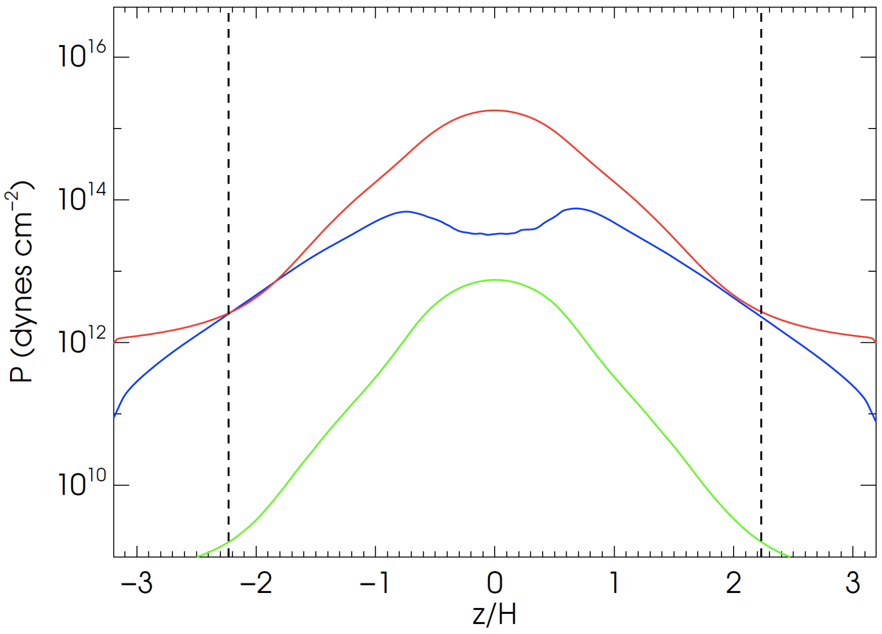
$$v_\mathrm{turb} \sim v_\mathrm{A} \sim \left(\frac{P_\mathrm{mag}}{P_\mathrm{rad}}\right)^{1/2} \left(\frac{P_\mathrm{rad}}{P_\mathrm{gas}}\right)^{1/2} c_\mathrm{gas}$$

Because photosphere regions generally have $P_{\mathrm{mag}} > P_{\mathrm{rad}}$, expect *bulk* Comptonization off of the *turbulence* to dominate thermal Comptonization in the scattering-dominated atmosphere when $P_{\mathrm{rad}}/P_{\mathrm{gas}} > \mathrm{m_p}/\mathrm{m_e} \sim 2000$.

A Crude Disc Spectrum Calculation

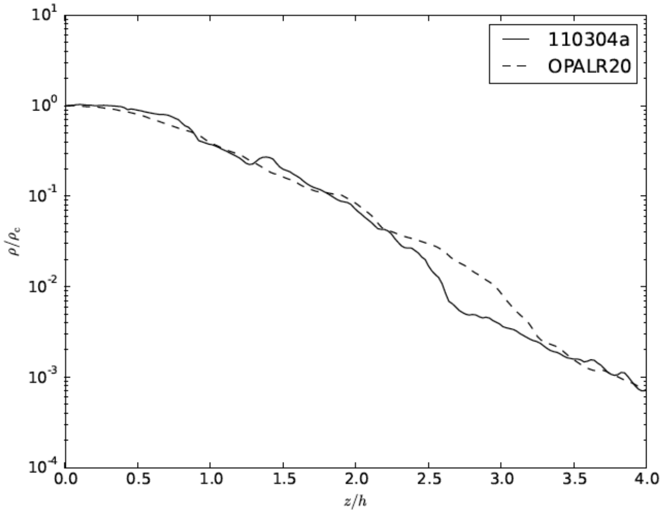
As a first guess, take a single epoch of our most radiation pressure dominated, stratified shearing box simulation (Hirose, Krolik & Blaes 2009), scale velocities and pressures up according to NT73 equations, and Monte Carlo the emergent photon spectrum at each radius, and fold through a relativistic ray tracing code (Kerrtrans).



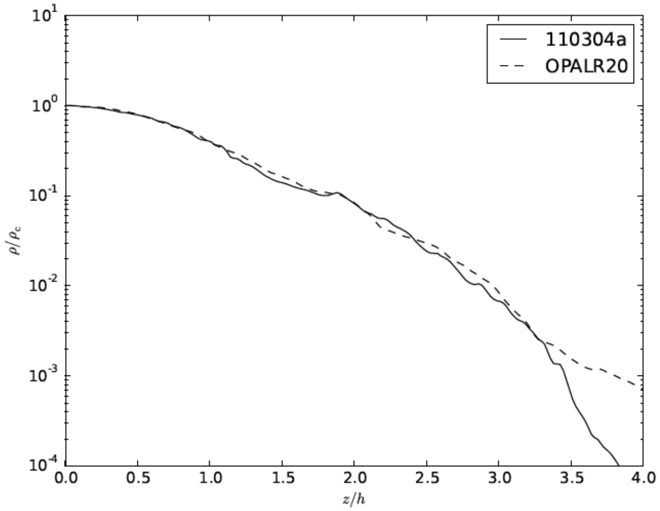


Radiation, magnetic, gas pressure profiles

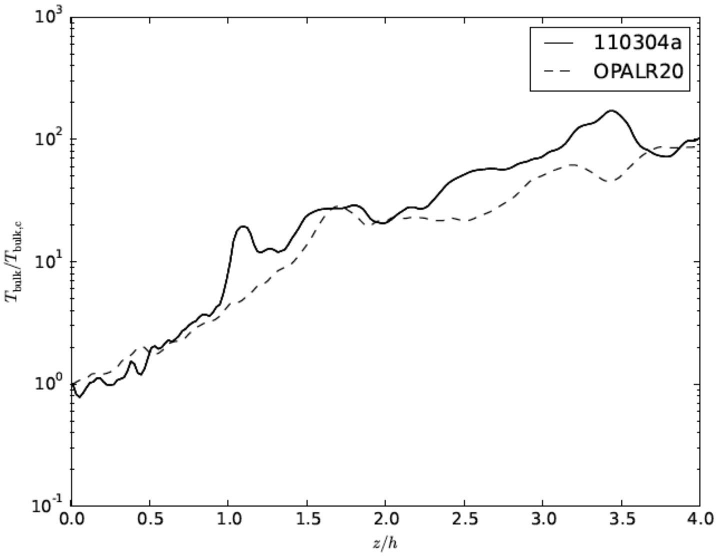
Stratified Shearing Boxes Appear to be Scalable



Scaled
Density
Profiles
At Two
Different
Epochs

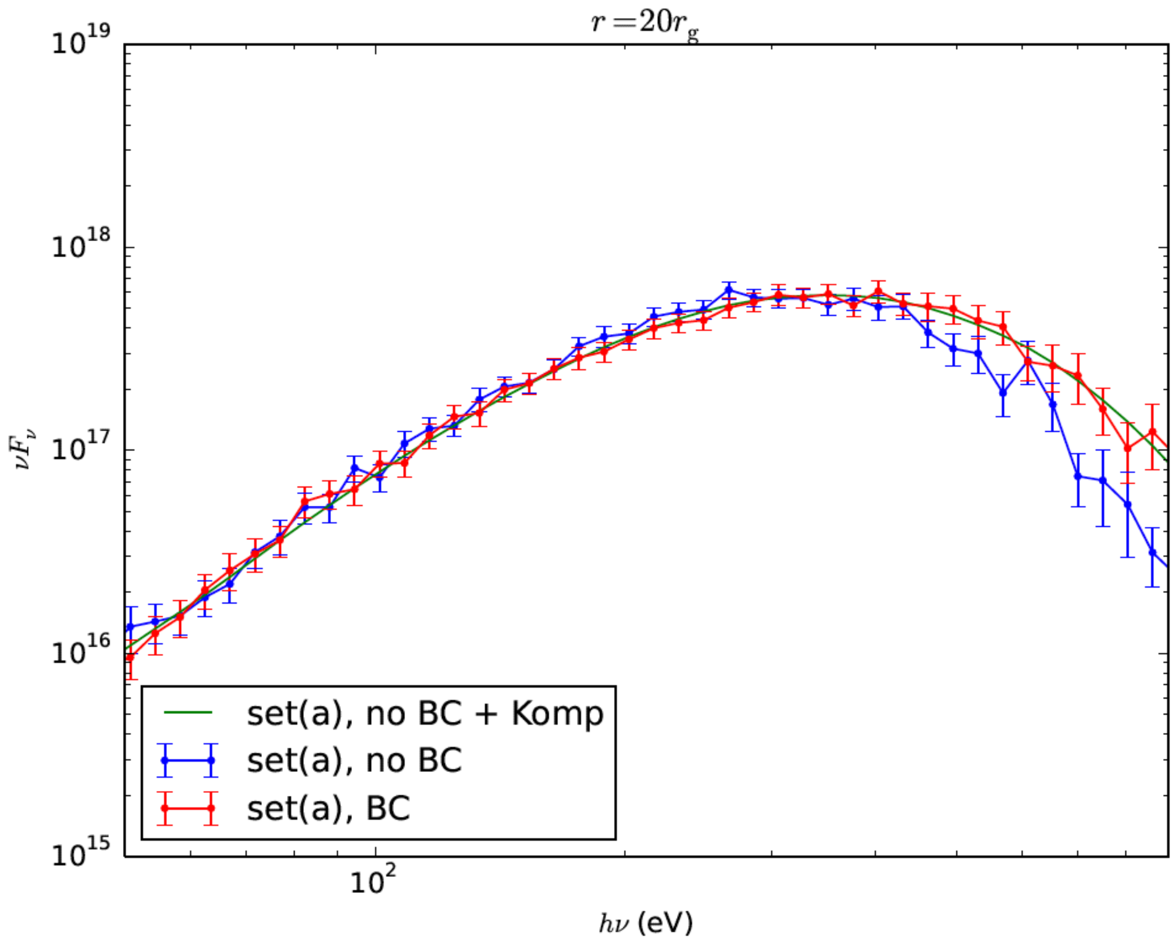


Scaled Mean
Square Turbulent
Kinetic Energy
Profiles



-Kaufmann, Blaes & Hirose 2017

Spectra from (scaled) stratified shearing box

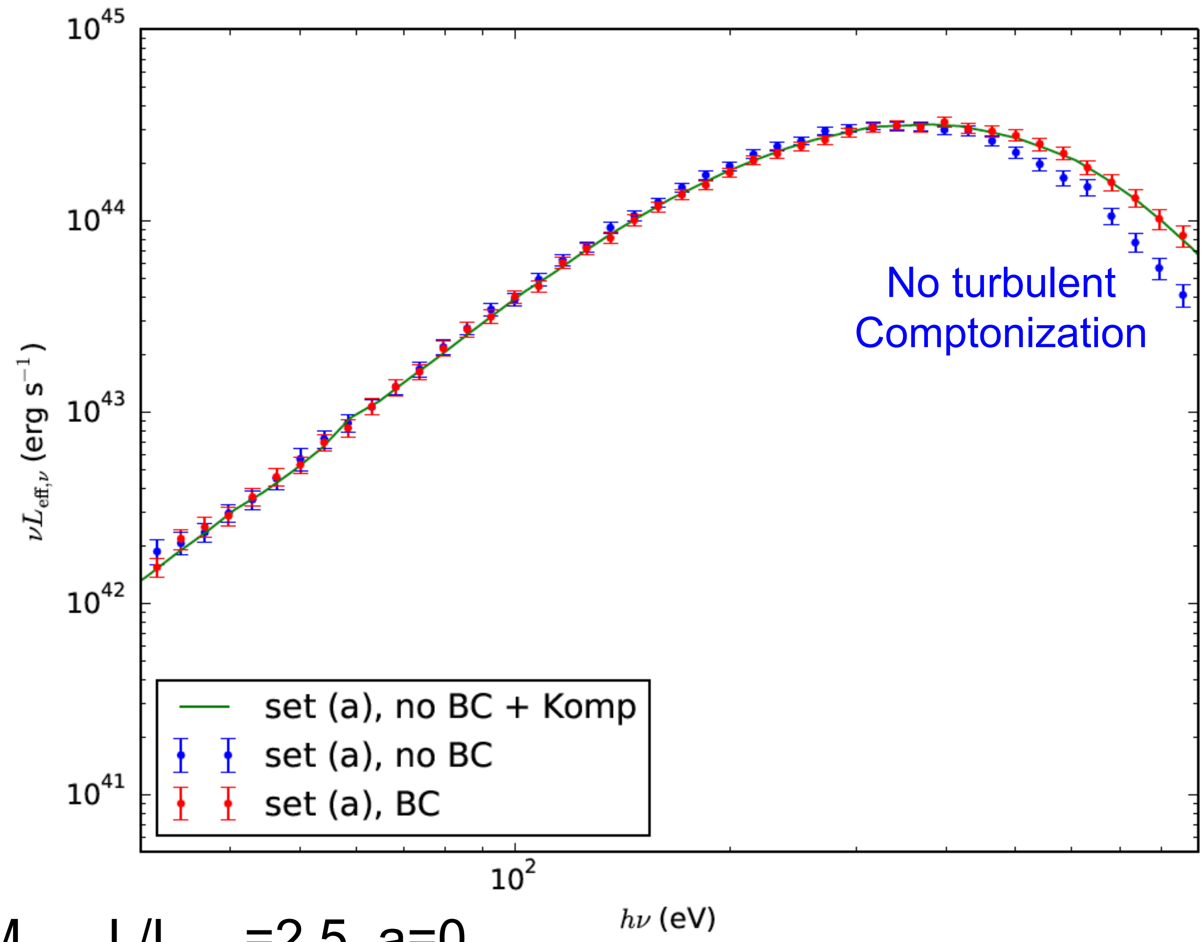


M=2X10^6 M_{sun}, L/L_{Edd}=2.5, a=0

Komp fit parameters: kT=0.14 keV, τ=15

-Kaufman, Blaes & Hirose (2017)

A Simple Disk Model Spectrum Around a Schwarzschild SMBH



With turbulent Comptonization

No turbulent Comptonization

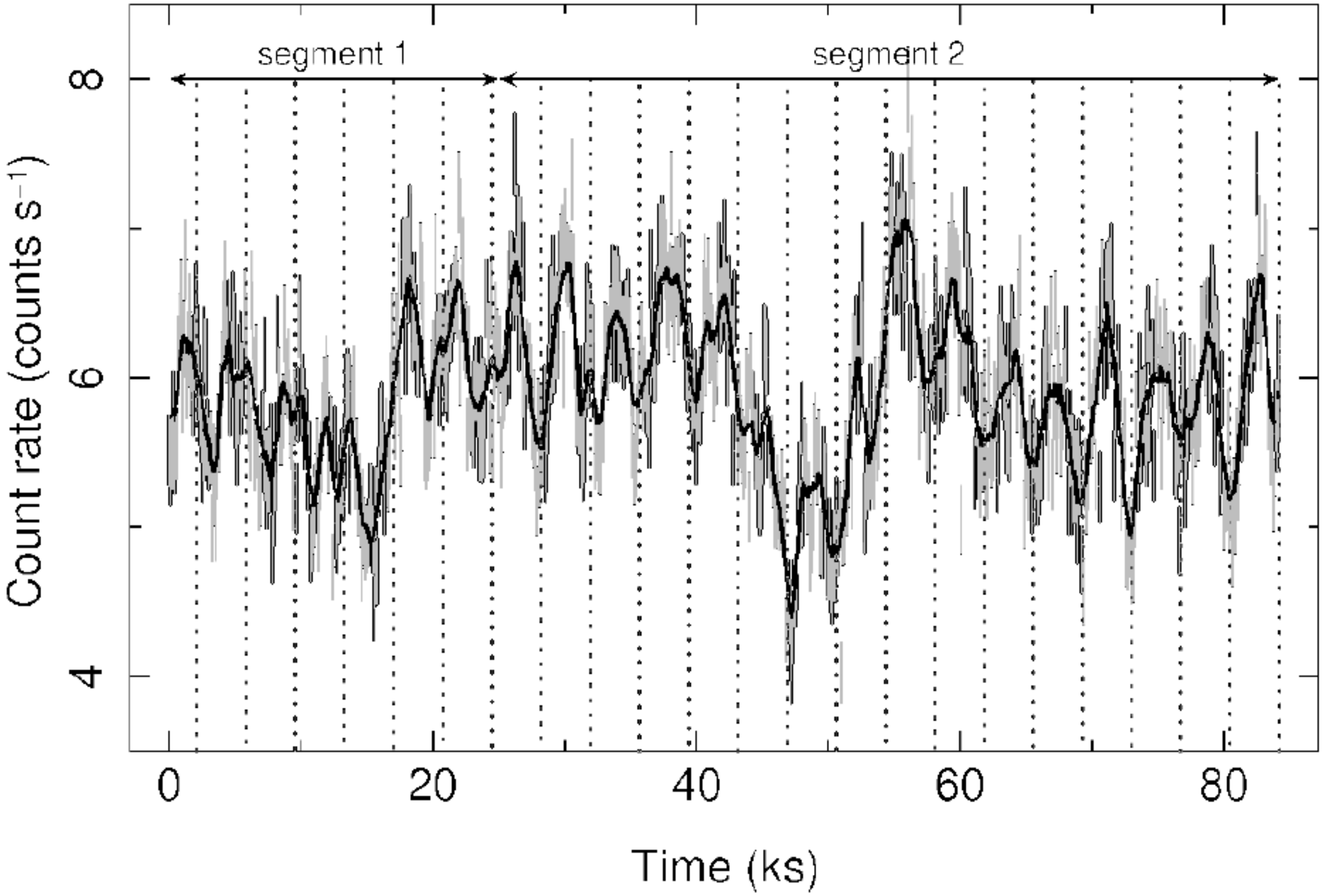
$M=2\mathrm{X}10^6\ M_{sun}$, $L/L_{Edd}=2.5$, $a=0$

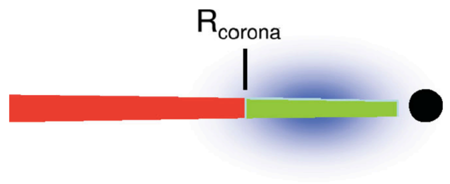
Komp fit parameters: $kT=0.14$ keV, $\tau=15$, $r_{cor}=20\ r_g$, $y=0.26$

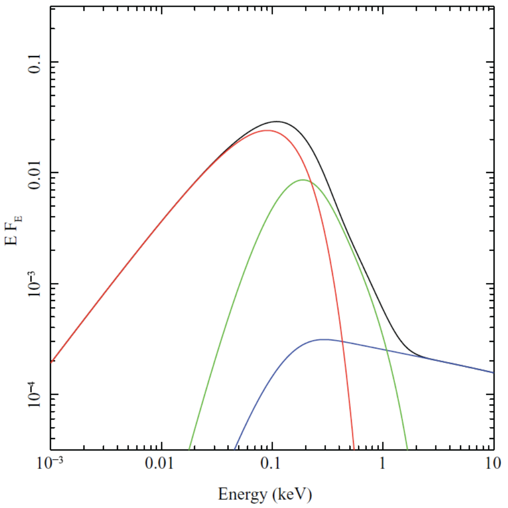
-Kaufmann, Blaes & Hirose 2017

RE J1034+396

-A Narrow Line Seyfert 1 that clearly shows a convincing QPO (Gierlinski et al. 2008)







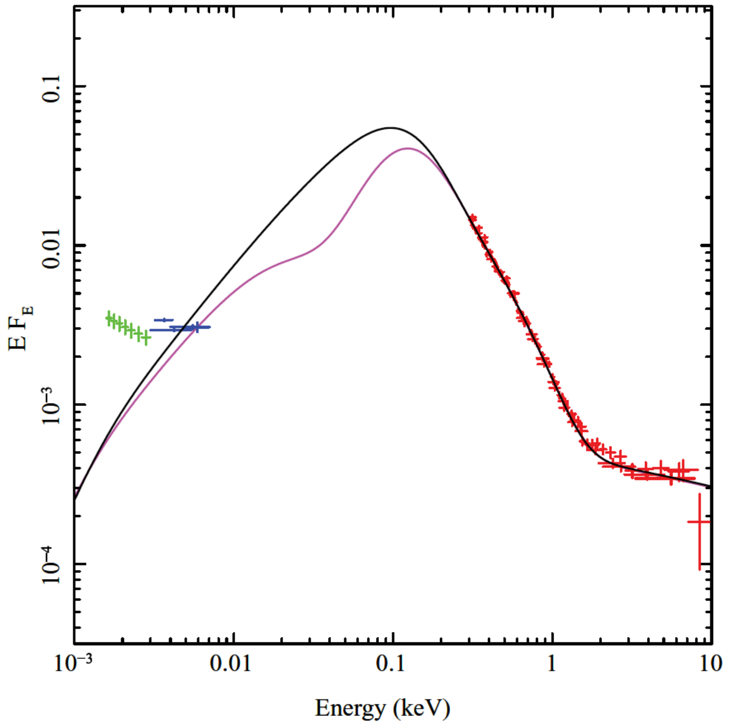


Table 1. Details of fits to the NLS1 RE 1034+396 using the intrinsic Comptonization model for the soft excess. The first line has $f_{\rm col} = 1.0$ while the second is for $f_{\rm col} = 2.4$.

$N_{\rm H}$ (10^{20} cm^{-2})	$f_{\rm col}$	M (10^6 M$_\odot$)	$L/L_{\rm Edd}$	$r_{\rm corona}$ ($R_{\rm g}$)	$kT_{\rm e}$ (keV)	τ	Γ	$f_{\rm pl}$	χ^2/ν
1.7 ± 0.7	1.0	$1.2^{+0.1}$	$5.0^{+0.7}_{-0.6}$	31^{+14}_{-9}	0.23 ± 0.03	11 ± 1	2.2	0.05 ± 0.02	631/563
1.6 ± 0.6	2.4	$1.9^{+0.8}_{-0.1}$	$2.4^{+0.3}_{-0.6}$	100^{+*}_{-60}	0.23 ± 0.03	11 ± 1	2.2	0.05 ± 0.02	630/563

*indicates that the parameter is pegged at the upper/lower limit.

y=0.22

-Done et al. (2012)

Summary

- Luminous AGN accretion flows are radiation pressure dominated.
- Radiation dominated plasmas can be highly compressible and are likely characterized by strong density inhomogeneities.
- Radiation advection by buoyant concentrations of magnetic field is likely to contribute significantly to overall thermal balance.
- Radiation pressure dominated disks with electron scattering opacity appear to be thermally unstable in both local and global simulations. Iron opacity may be a stabilizing mechanism in AGN (or strong magnetic fields?).
- Radiation pressure driven outflows almost certainly alter the disk structure. This is not a constant Mdot flow.
- The most naïve rescalings of existing shearing box simulations into a zero inner stress NT73 disk produce conditions with enough turbulent y-parameter to explain strong soft X-ray excesses in NLSy1's.

The Immediate(!) Future

Three developments were the motivation for this program:

(1) The fabulous observational data

(2) The incorporation of thermodynamics in MHD simulations

(3) The computational capacity to do GLOBAL simulations with thermodynamics

The last has just begun to happen for protoplanetary disks (talks by Lesur and Bai), is beginning to happen for CV disks (Stone presentation; Jiang, Coleman…), and is also happening for luminous black hole disks (talks by Sadowski, Jiang).