RADIATION FROM ACCRETION ONTO BLACK HOLES

Accretion via MHD Turbulence: Themes

- Replacing dimensional analysis with physics

  MRI stirs turbulence; correlated by orbital shear; dissipation heats gas; gas radiates photons

- No universal ratio between stress and pressure

  systematic spatial gradients, local fluctuations; pressure not unique dimensionally

Accretion via MHD Turbulence: Open Questions

- Magnetic saturation? Dependence on microphysics? Numerical convergence?
- Radiation-driven dynamics: Non-diffusive effects? Relation to mean stress? Global effects?
- Observable signatures of GR effects?
- Jets: Energy source? Spin-dependence? Magnetic intensity regulation? Matter content?

Radiation-Driven Dynamics

Radiation-Dominance the Natural State of the Interesting Portions of Bright Disks

(Shakura & Sunyaev 1973)

Radiation pressure exceeds gas pressure for

$$r/r_g < 170(L/L_E)^{16/21}(M/M_\odot)^{2/21}$$

That is, for the most interesting
parts of all bright accretion disks
around black holes

α – Model Predicts Thermal Instability When $p_r > p_g$

Shakura & Sunyaev 1976

In the α model, $\int dz\, Q \sim \Omega \int dz\, T_{r\phi} \sim \alpha p_r h$

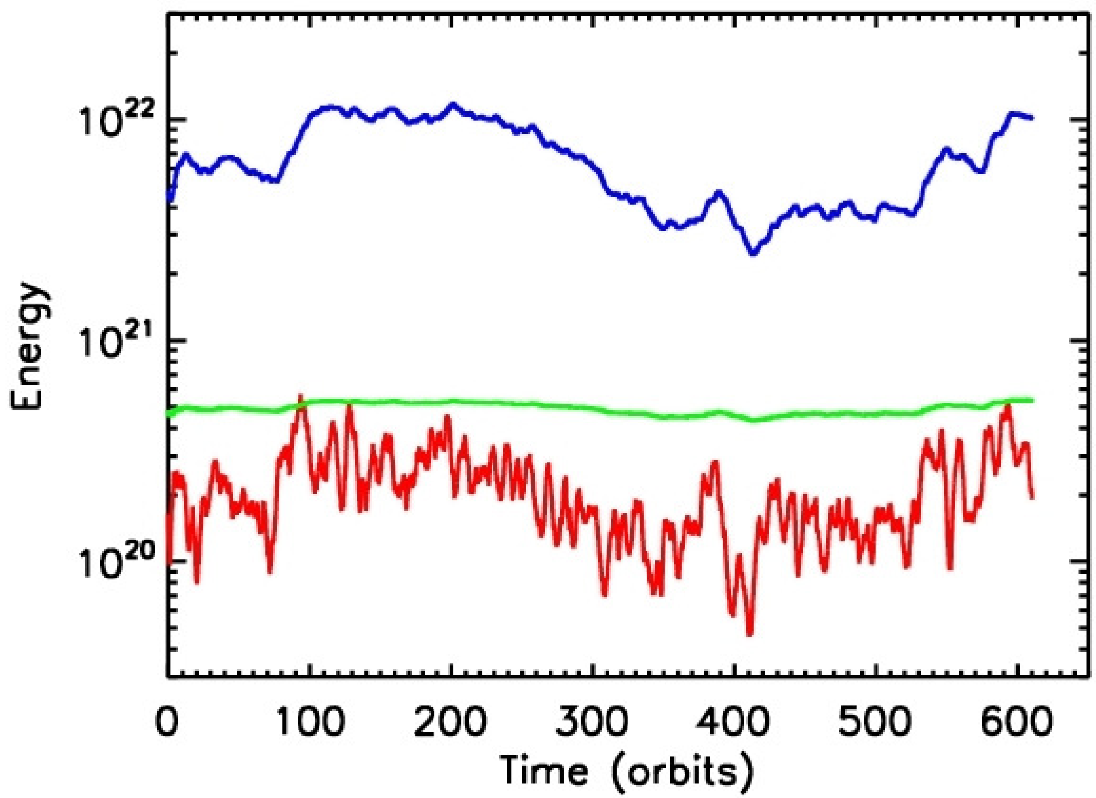
When radiation pressure dominates, $h \propto \mathcal{F} = \int dz\, Q$

And $p_r \sim Q t_{\rm cool} \sim Q(h/c)\tau \sim (\tau/c) \int dz\, Q$

Thermal Instability

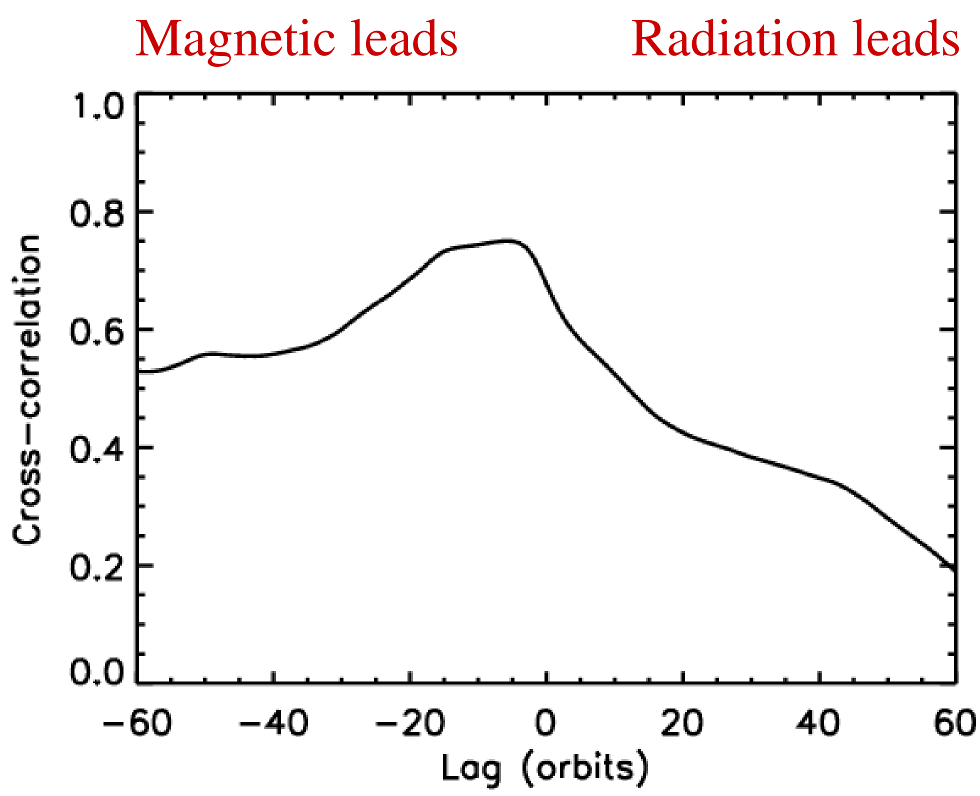
But Even When $p_r \sim 10p_g$, No Runaway!

Hirose, K. & Blaes (2009)



$t_{cool} = 15$ orbits

Stress Drives Pressure



Magnetic Energy vs. Radiation Energy

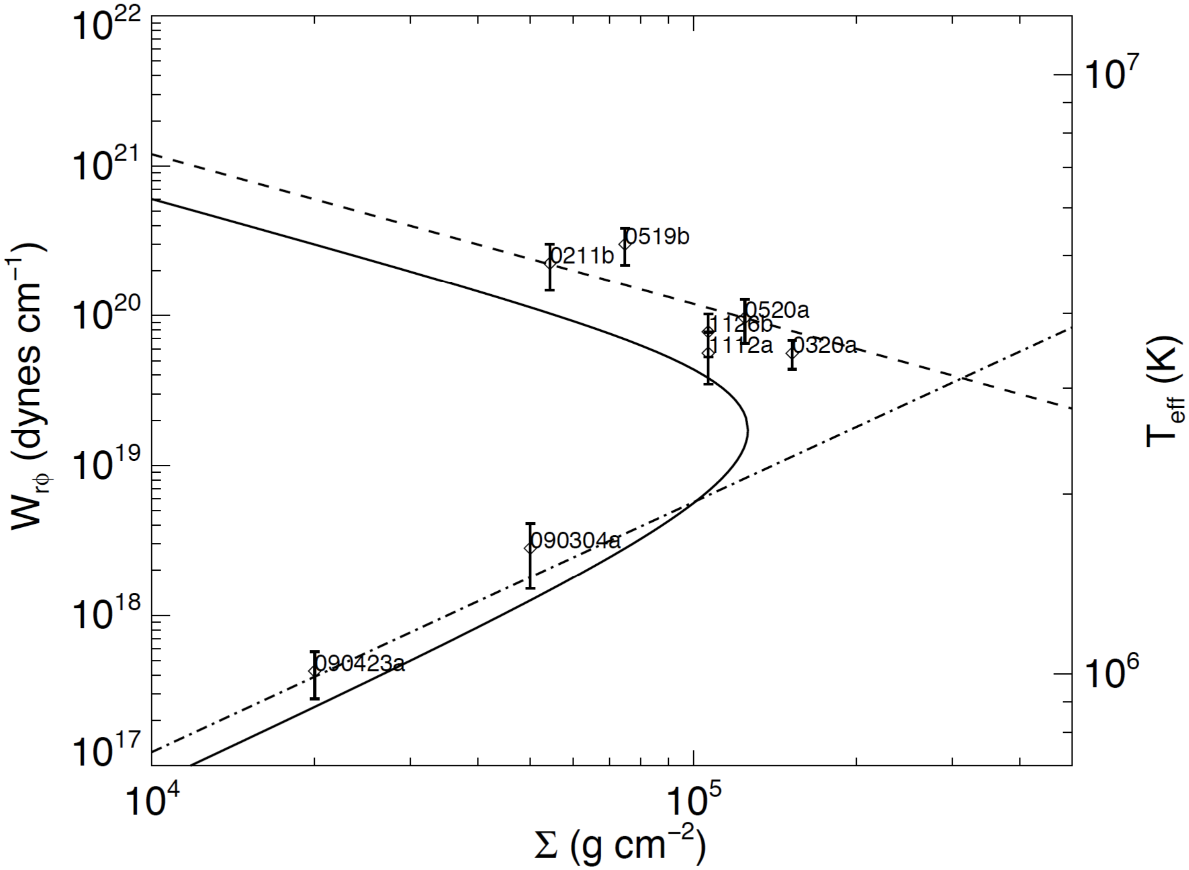
Is the α–model Dimensional Analysis Unique?

Consider $c\Omega/\kappa$: erg/cm^3 (Shakura & Sunyaev 1976)

Dissipation = $c\Omega^2/\kappa$ required for hydrostatic balance

Hydrostatic balance enforced on dynamical timescale, faster than thermal balance: dynamics can control thermodynamics

Averaging over T >> t_{cool} Restores α



And hints at inflow clumping instability

(Lightman & Eardley 1974)

Observable (?) GR Effects:
Stress Near the ISCO

Global Conservation Laws: the Novikov-Thorne Model

Content:

- Axisymmetric, time-steady, thin enough for vertical integration
- Prompt, local radiation of dissipated energy
- Energy and angular momentum conservation in GR setting
- Determines radial profiles of stress, dissipation rate (required by mis-match between energy flow of accretion, work done by stress)

$$\int dz\, T_{r\phi} = \frac{1}{2\pi}\dot{M}\Omega(r)\left[1 - j_{in}/(r^2\Omega)\right]$$

$$\int dz\, Q = \frac{3}{4\pi}\dot{M}\Omega^2(r)\left[1 - j_{in}/(r^2\Omega)\right]$$

(in the non-relativistic limit)

The boundary condition j_{in} makes all the difference!

Choosing j_{in}

- Traditional choice: $j_{in} = u_\phi(\text{ISCO})$, implying $T_{r\phi} = 0$ at and inside the ISCO
- This hydrodynamically plausible choice determines the radiative efficiency as a function of spin as well as the maximum temperature

- But could the stresses continue?

Exception! Magnetic Fields

E.g., see Thorne (1974):

“Magnetic fields attached to the disk may reach into the horizon, producing a torque on the hole (Ya.B. Zel’dovich and V.F. Schwartzman, private communication)…In the words of my referee, James M. Bardeen, ‘It seems quite possible that magnetic stresses could cause large deviations from circular orbits in the very inner part of the accretion disk and change the energy-angular-momentum balance of the accreting matter by an amount of order unity.’ ”

Magnetic fields can stretch across the marginally stable region, exerting large stresses even when connected to matter of little inertia

Estimate Magnetic Stress in Plunging Region

- Time-steadiness
- Mass conservation
- Normalizing to conditions at “turbulence edge”

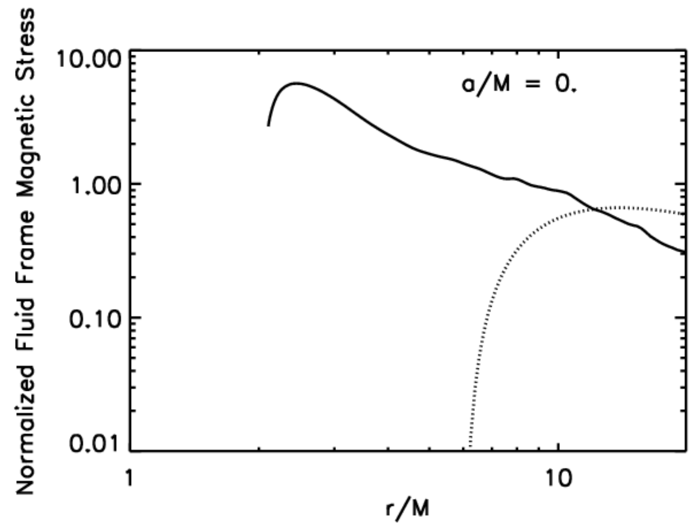
$$\frac{B^2}{4\pi\rho v^2} \approx \frac{\dot{j}}{\dot{j}_{turb}} \left(\frac{B}{B_{turb}}\right)^2 \frac{v_r}{v_\phi} \left(1 - \dot{j}_{in} \big/ \dot{j}_{turb}\right)$$

Published Simulations Differ: Why?

K., Hawley & Hirose (2005):

a/M = 0; j_{ISCO} = 3.464

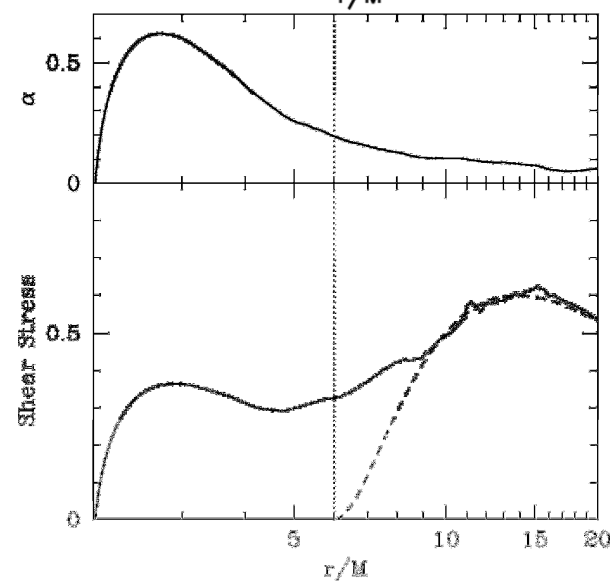
H/R ~ 0.09—0.13



Shafee et al. (2008):

a/M = 0; j_{ISCO} = 3.464

H/R ~ 0.06—0.08



Prerequisites for a Clean Determination

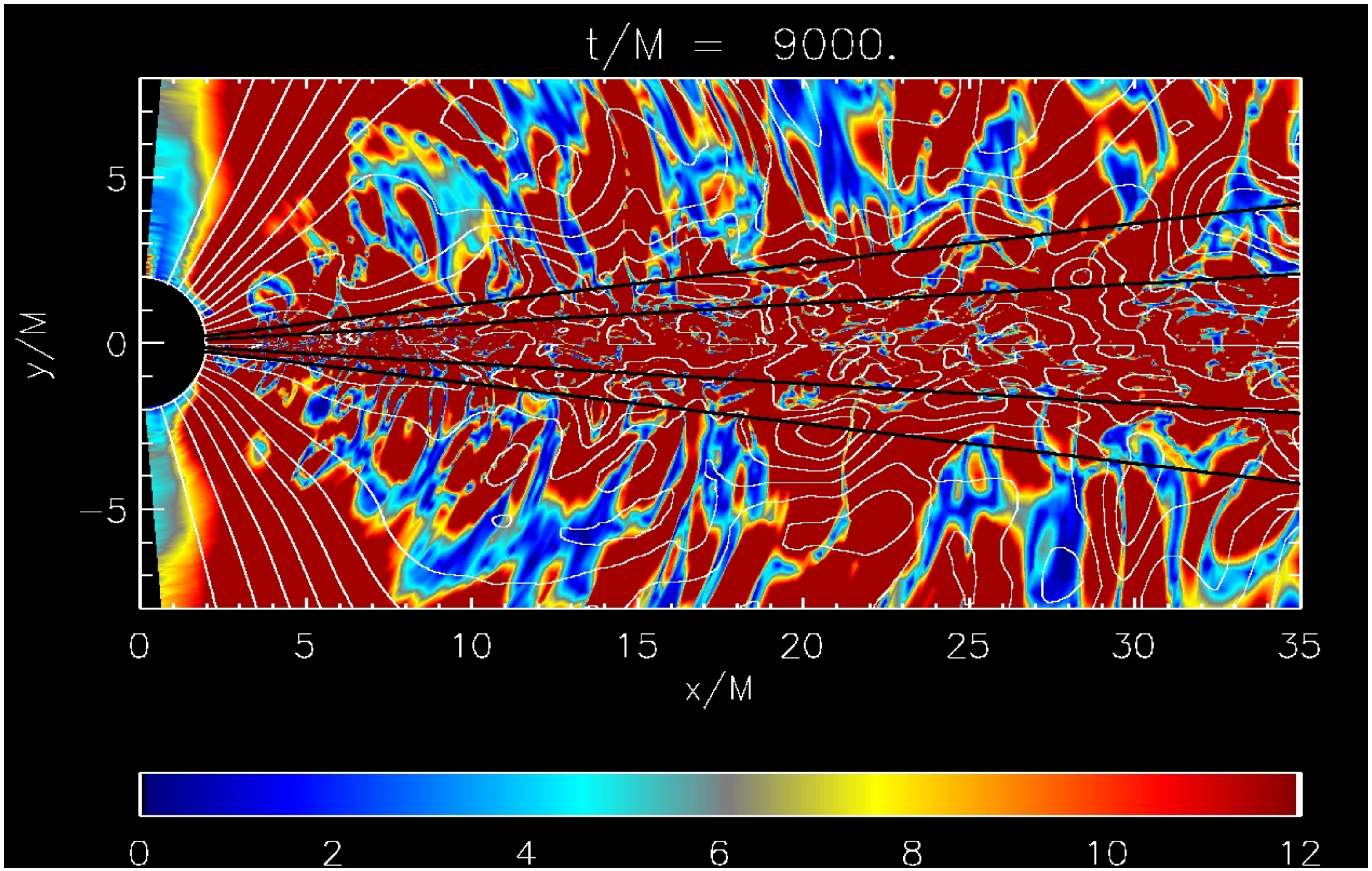
(Noble, K. & Hawley 2009, in prep.)

- Adequate resolution of MRI throughout the disk and at all times ($\lambda_{MRI} / \Delta z > 6$)
- Adequate azimuthal extent (> 1 radian)
- Genuine inflow equilibrium: time-steady M(<R) and $j_{in,\ net}$; T >> fluctuation timescale
- Initial condition reasonably close to steady-state
- For scaling in one variable, hold others fixed and ensure that variable has specified value

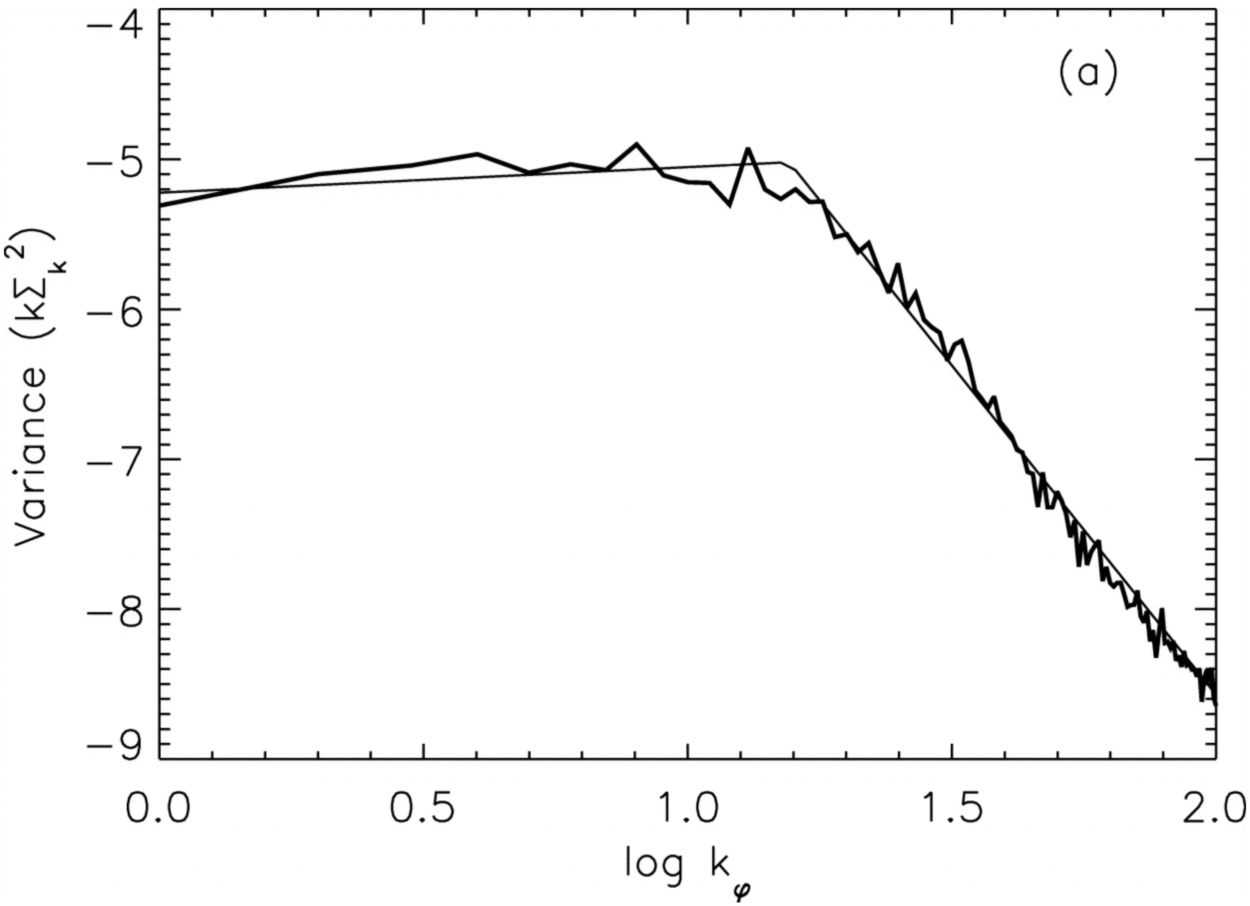
Specific Program

- Conservative algorithm
- Optically-thin cooling regulates H/R: $\nabla_\nu T^\nu_\mu = -\mathcal{L} u_\mu$
- Highest practical resolution: typical $\lambda/\Delta z \sim 20$
- Time-dependent M(<R) departures < 10%
- Time-steady $j_{in,net}$
- H/R=0.06, 0.10, 0.17

Resolution Quality: $\lambda_{MRI} / \left[\sqrt{g_{\theta\theta}}\Delta\theta\right]$

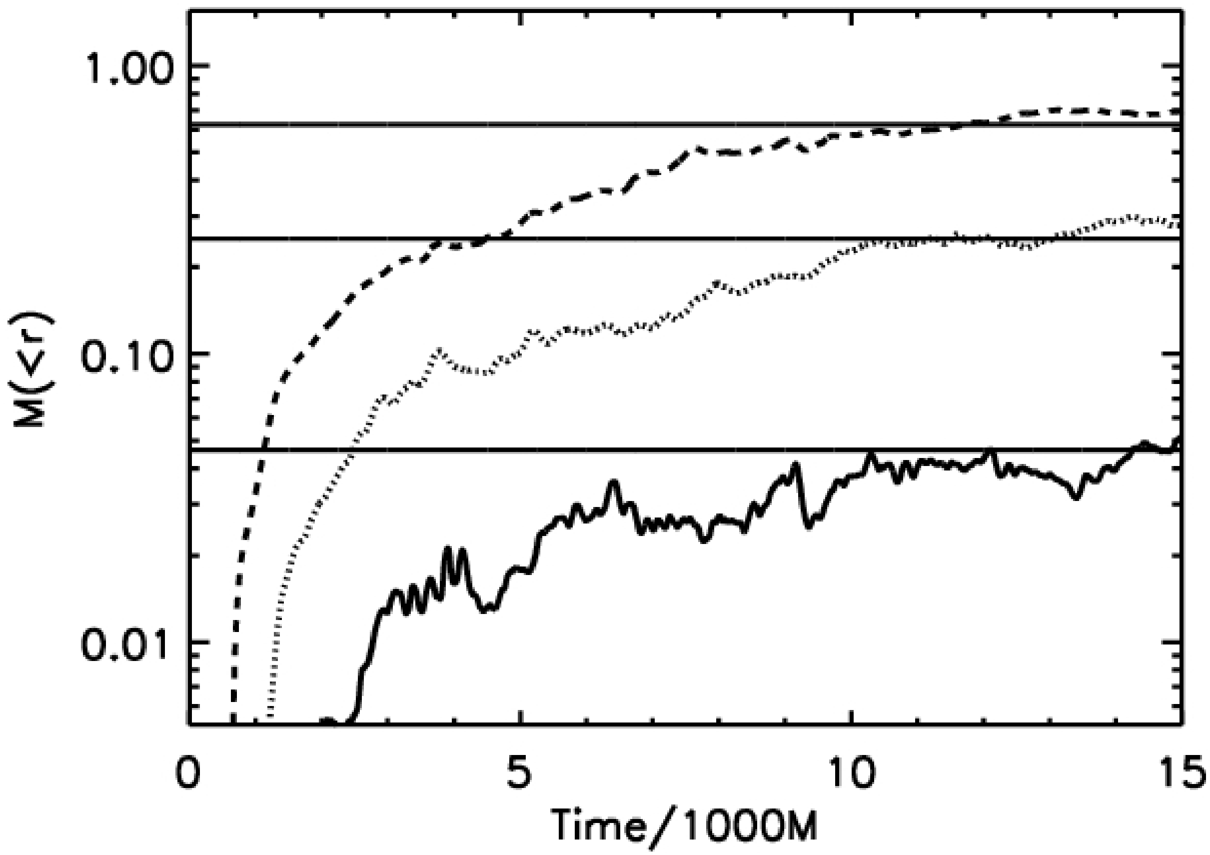


Importance of Azimuthal Extent



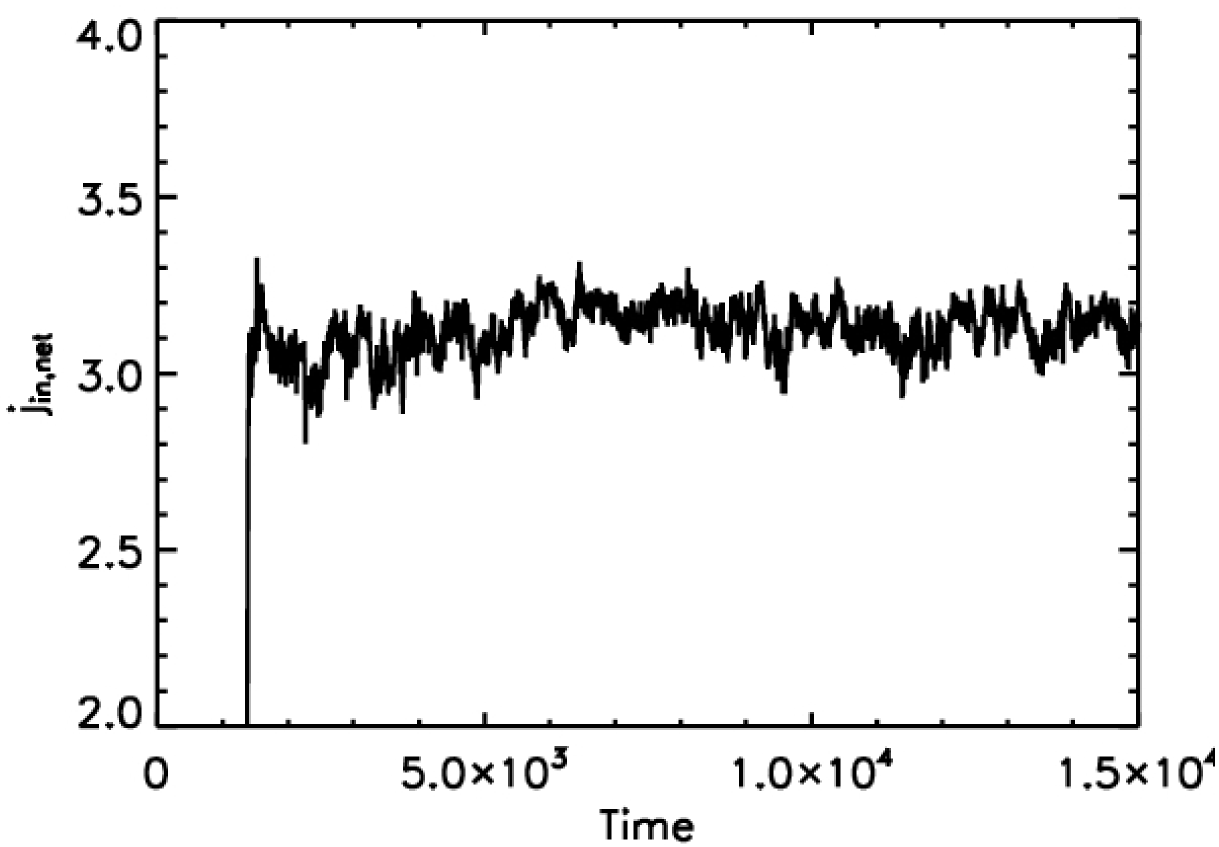
Schnittman, K. & Hawley (2006)

Inflow Equilibrium



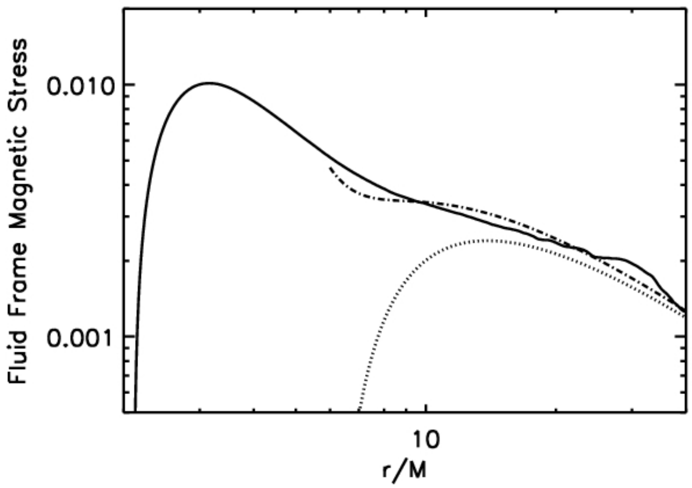
H/R = 0.06

Angular Momentum Flux Equilibrium

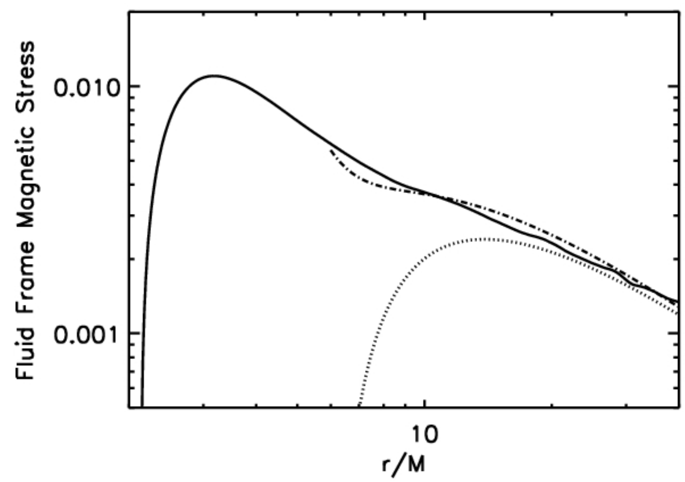


H/R = 0.06

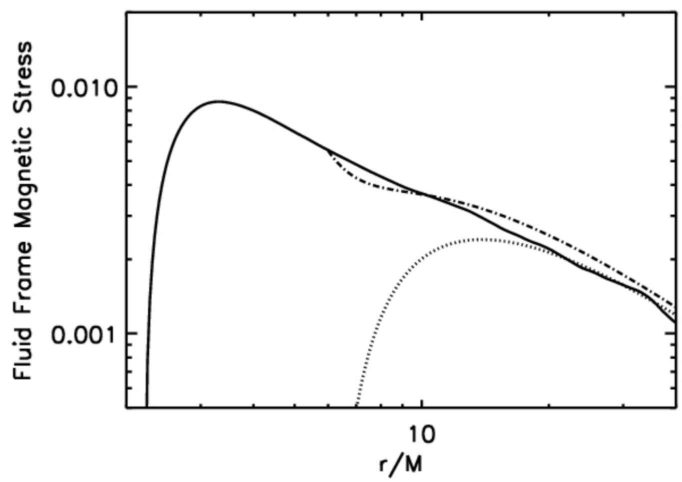
Fluid-Frame Stress Profiles



H/R=0.06



H/R=0.10



H/R=0.17

Collected a/M=0 Simulations

Code	Resolution $R \times \theta \times \phi$	Azimuthal domain	H/R	$j_{in,net}$ (j_{isco} = 3.464)
GRMHD	192x192x64	$\pi/2$	0.11—0.14	3.18
GRMHD(V)	256x256x64	$\pi/2$	0.10—0.15	~3.0
HARM3D(M)	512x128x32	$\pi/4$	0.06—0.07	3.32
HARM3D	912x160x64	$\pi/2$	0.061	3.13
HARM3D	512x160x64	$\pi/2$	0.10	3.08
HARM3D	384x160x64	$\pi/2$	0.17	2.93

Empirical Inferences

- Must take care with resolution, inflow equilibrium, etc.
- Azimuthal extent may matter
- Large-scale magnetic geometry significant

  (Vertical field vs. zero net-flux in GRMHD)
- Magnetic effects significant, increase slowly with H/R

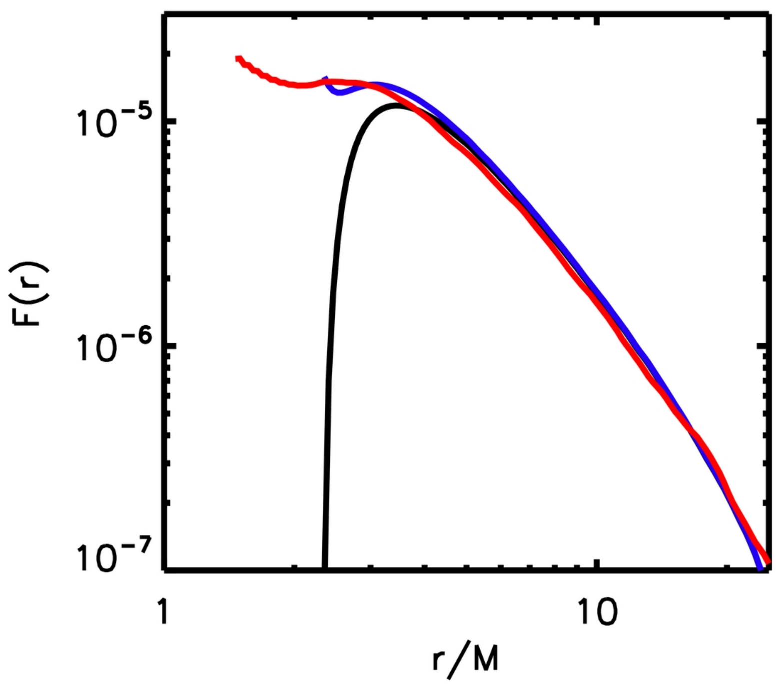
Physics Issues for Future Study

- Spin
- More magnetic topologies
- Realistic thermodynamics, H/R profile
- What are the physical mechanisms by which pressure or magnetic geometry influence ISCO-region stress?

GR Effects in Global Radiation Properties: Efficiency and Variability

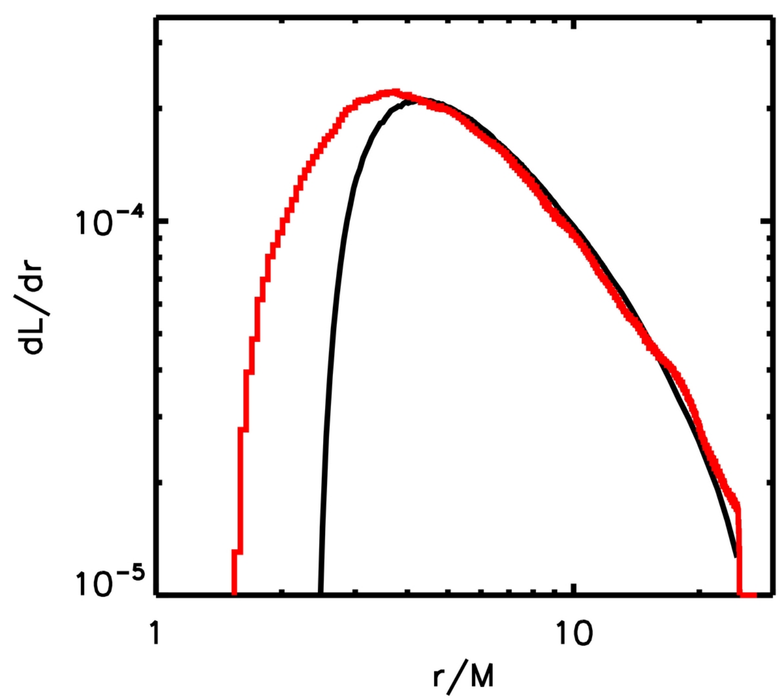
Fluid-frame Emissivity

(Noble, K. & Hawley 2009)



a/M=0.9, fluid-frame optically-thin emissivity, $t_{cool} \sim 1/\Omega$

Luminosity at Infinity



a/M=0.9, dL/dr after photon capture, red-shift

Net Radiative Efficiency

After GR ray-tracing, Doppler-shifting, etc.

$$\epsilon_{\mathrm{sim}} = 0.151$$

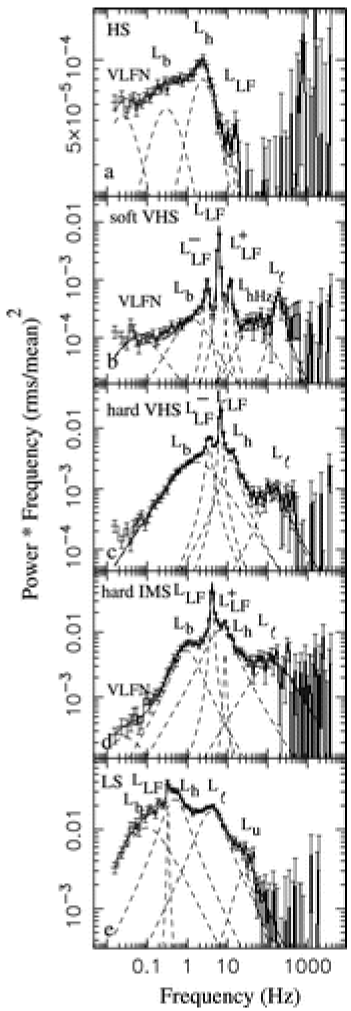
$$\epsilon_{\mathrm{NT}} = 0.143$$

$$h(r = 2M) \simeq 0.02$$

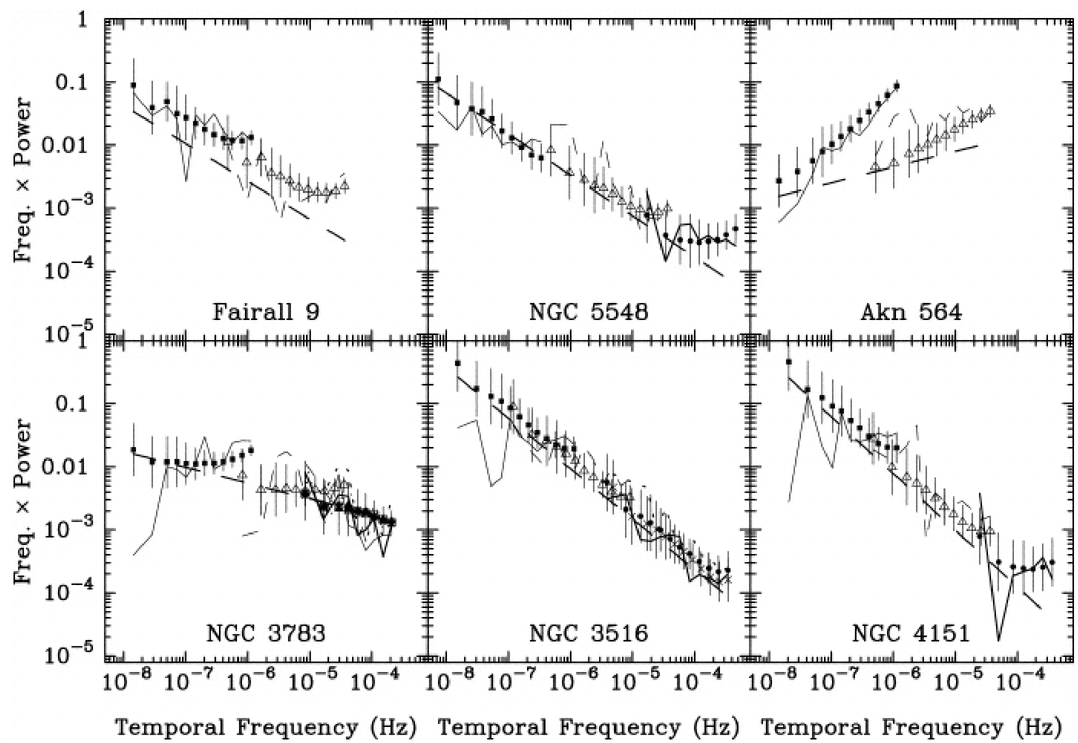
$$\frac{B^2}{8\pi\rho c^2}(r = 2M) \simeq 0.03$$

Ubiquitous Variability of Accreting Black Holes

Galactic binaries, hard state
(Klein-Wolt & van der Klis 2008)



AGN (Markowitz et al. 2003)



Key Physical Issues

- Diffusive smoothing of radiative fluctuations in disk body
- Statistics of magnetic reconnection events in disk corona
- Supply of seed photons to corona, Compton cooling
- GR ray-tracing, time-delays

Key Physical Issues

- Diffusive smoothing of radiative fluctuations in disk body:
  Requires radiation/MHD code
- Statistics of magnetic reconnection events in disk corona:
  Compute in optically-thin region
- Supply of seed photons to corona, Compton cooling:
  Toy-model; computable in near-future
- GR ray-tracing, time-delays
  Real calculation

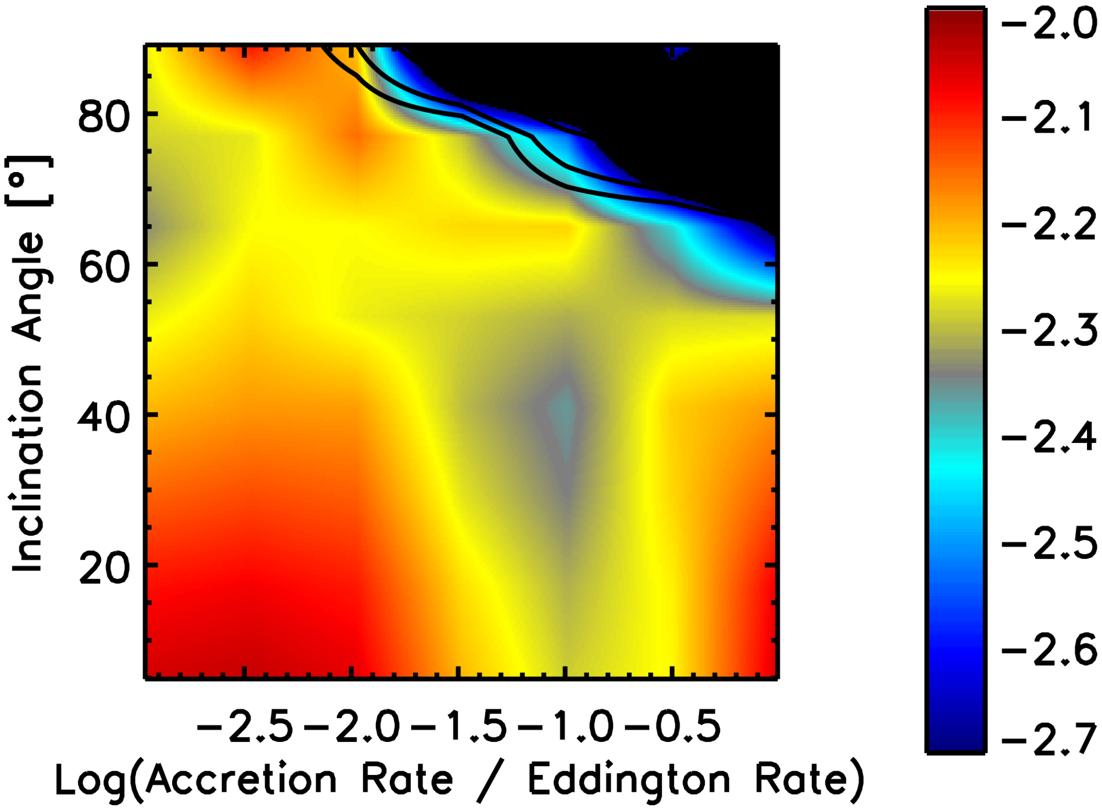
Light-Curve Fluctuations

(Noble & K. 2009)

Toy-model cooling function

$$\nabla_\nu T^\nu_\mu = -\mathcal{L} u_\mu$$

Truly optically thin regions only $(\tau \propto \dot{m})$



Result: power-law power spectrum, index ~ -2

Summary

- Radiation-dominated disks are thermally **stable**, but may exhibit new physics on inflow timescale
- Magnetic stresses at ISCO can be important: weakly-dependent on disk thickness, also likely dependent on other parameters
- Radiative consequences can be approximately quantified