Three Dimensional GRMHD Simulations: Stress at the ISCO

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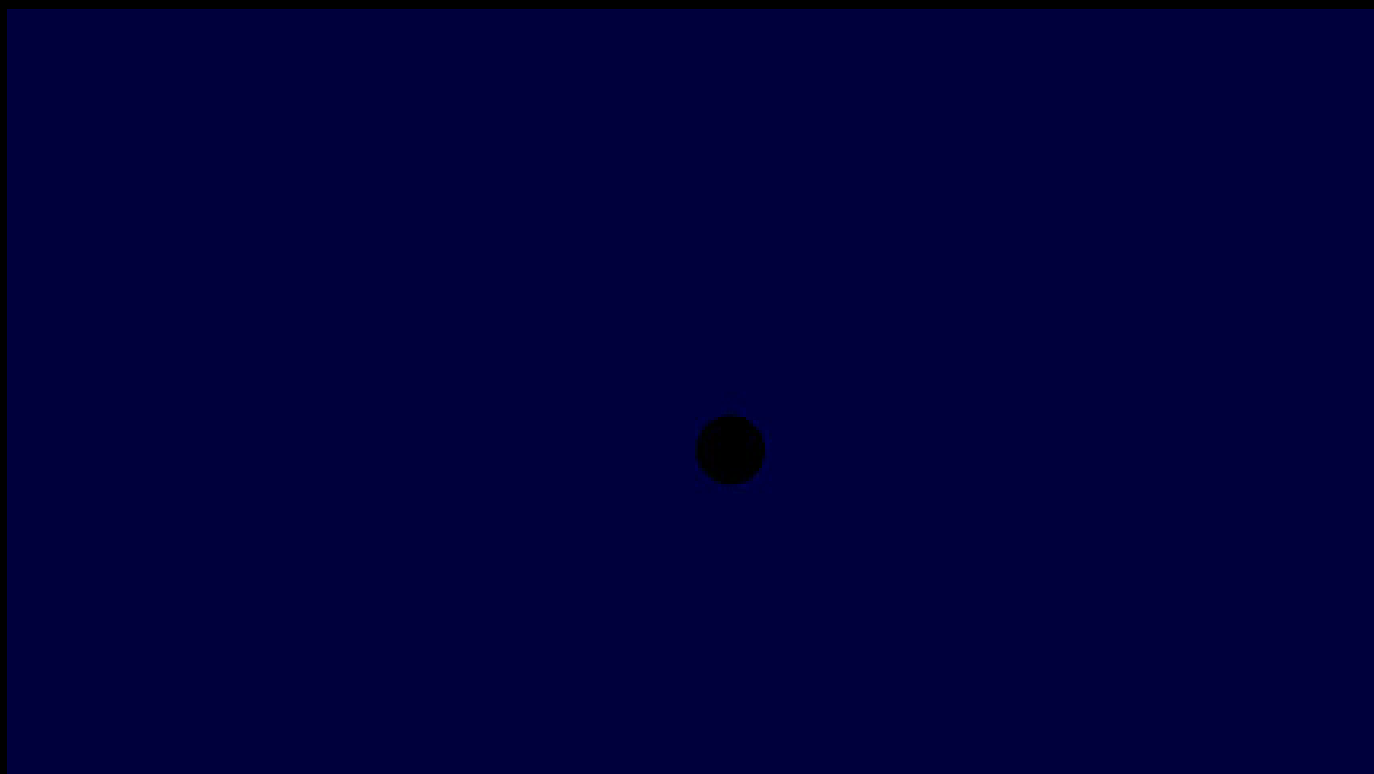


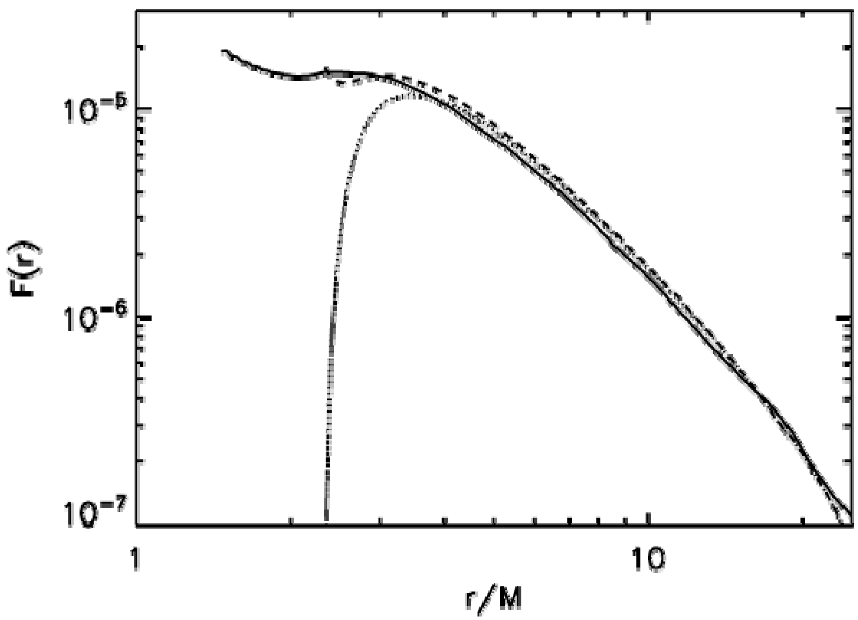
The Importance of MHD Stress at the ISCO

MHD Stress at the ISCO

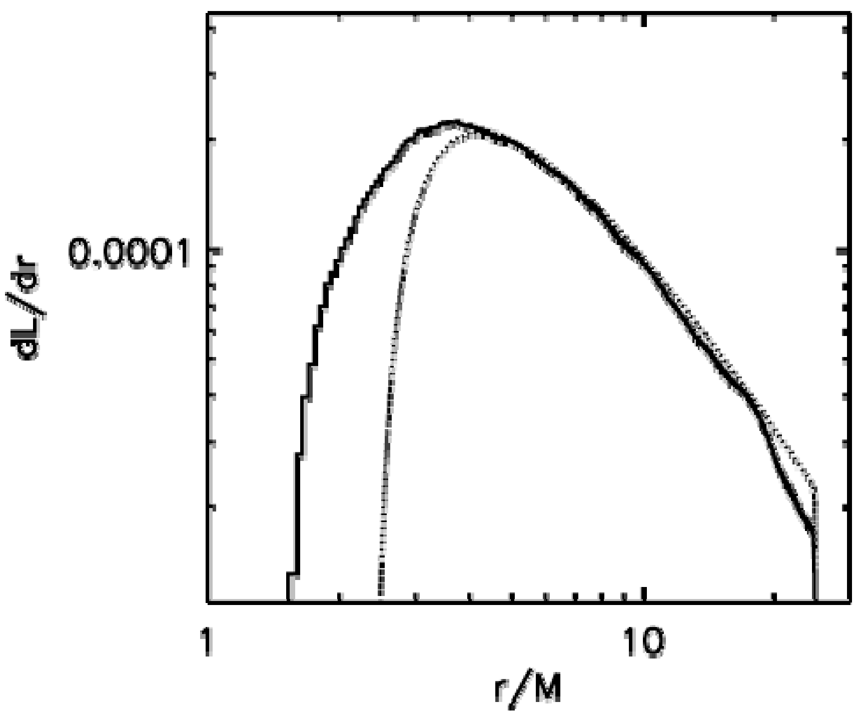
- Total disk luminosity depends on how much angular momentum can be removed from the accreted gas – in disk theory this is determined by inner boundary condition on angular momentum flux
- Conventional disk theory (Shakura-Sunyaev, Novikov-Thorne) assumes stress goes to zero at the Innermost Stable Circular Orbit (ISCO) – this creates a direct relationship between accretion efficiency and black hole spin, a/M
- However: Magnetic torque can act across and inside ISCO potentially increasing efficiency (Gammie 1999; Krolik 1999)
- Global simulations find enhanced stress at the ISCO under many circumstances
- Does enhanced stress depend on H/R? Other factors?

Potential Importance: Enhanced Luminosity from Enhanced Stress

a/M = 0.9 simulation



Radiated Flux per unit area



Luminosity received at infinity per unit radial coordinate

Noble et al (2009)

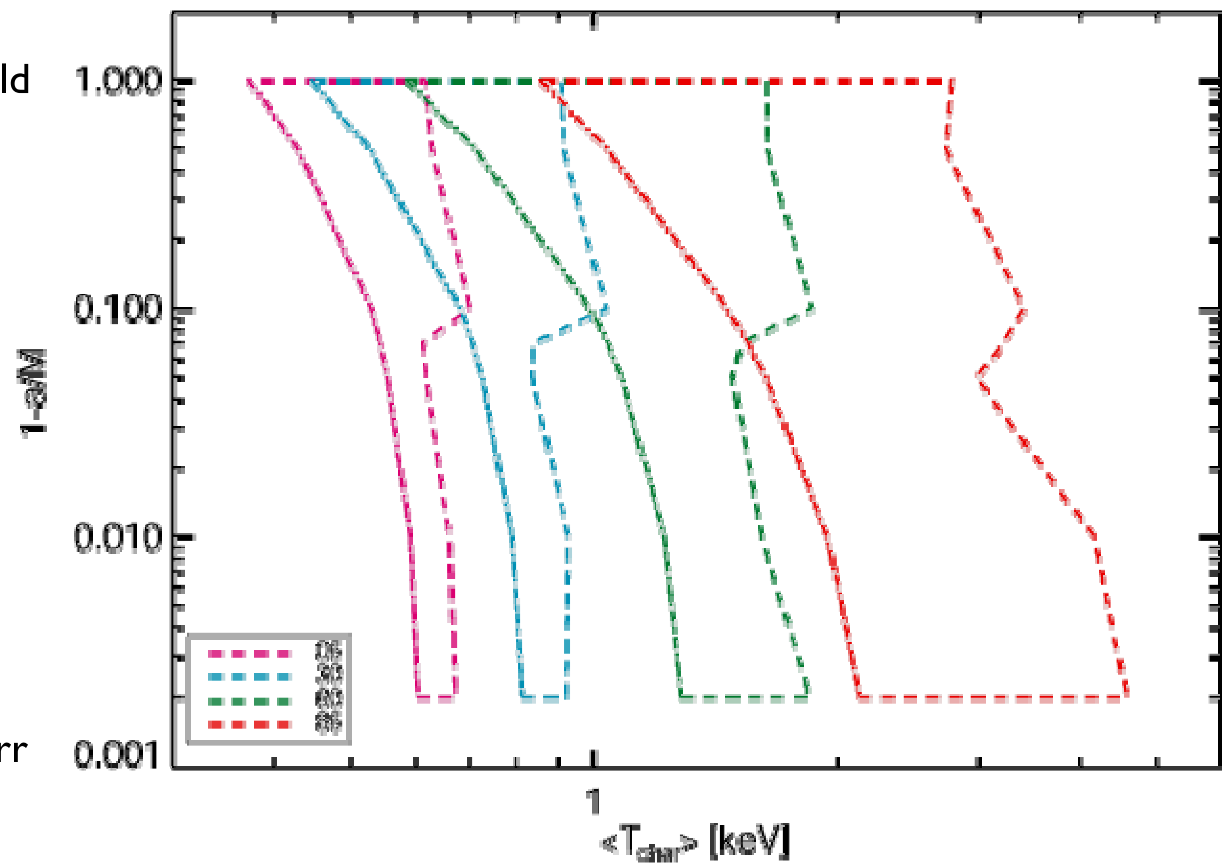
Estimated Accretion Efficiency from Enhanced Stress

a/M	η_{NT}	η_{MHD}
0.0	0.055--0.056	0.067--0.07
0.5	0.077--0.079	0.13--0.14
0.9	0.137--0.145	0.16--0.18
0.998	0.250--0.290	0.29--0.41

Potential Importance: Characteristic Temperature as a Function of Spin and Inclination in X-ray Binaries

Schwarzschild

Maximal Kerr



Beckwith et al 2008

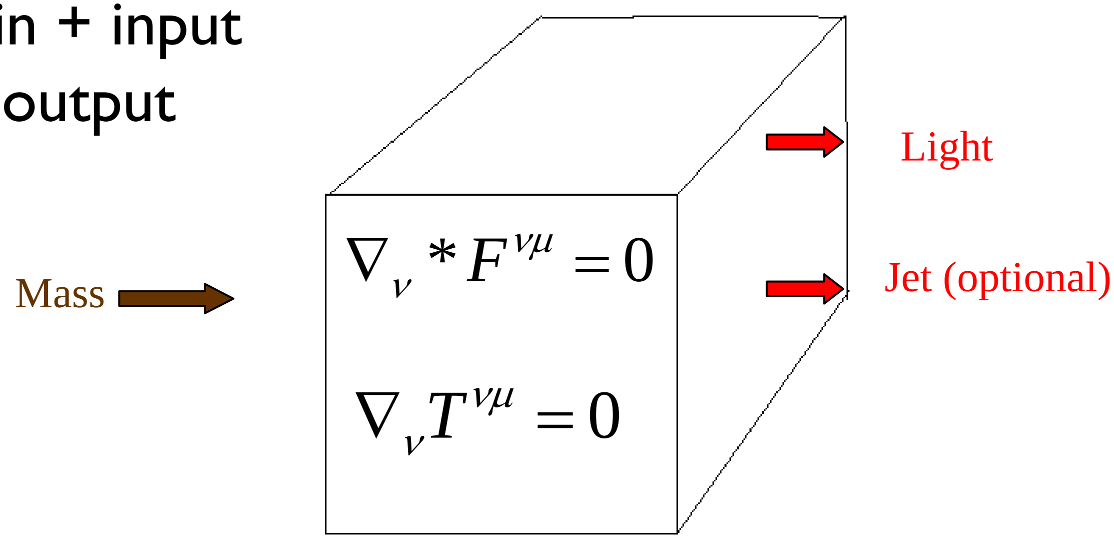
Potential Importance: Accreted Angular Momentum and Spin of the Hole

- Internal torque in excess of the Novikov-Thorne level can reduce specific angular momentum of accreted matter below ISCO value
- Jet carries away some angular momentum – hole absorbs EM flux with negative spin
- Result is spin down for high values of a/M (De Villiers et al 2003; Gammie et al 2004)
- Gammie et al (2004) obtained limit a/M ~0.93 for one set of models

Global Three Dimensional GRMHD Simulations

The Goal of Accretion Simulations

- Let the equations determine the properties of accreting systems
- Black hole mass, spin + input fuel and field yields output



$$\nabla_\nu {}^*F^{\nu\mu} = 0$$

$$\nabla_\nu T^{\nu\mu} = 0$$

Global Black Hole Simulations

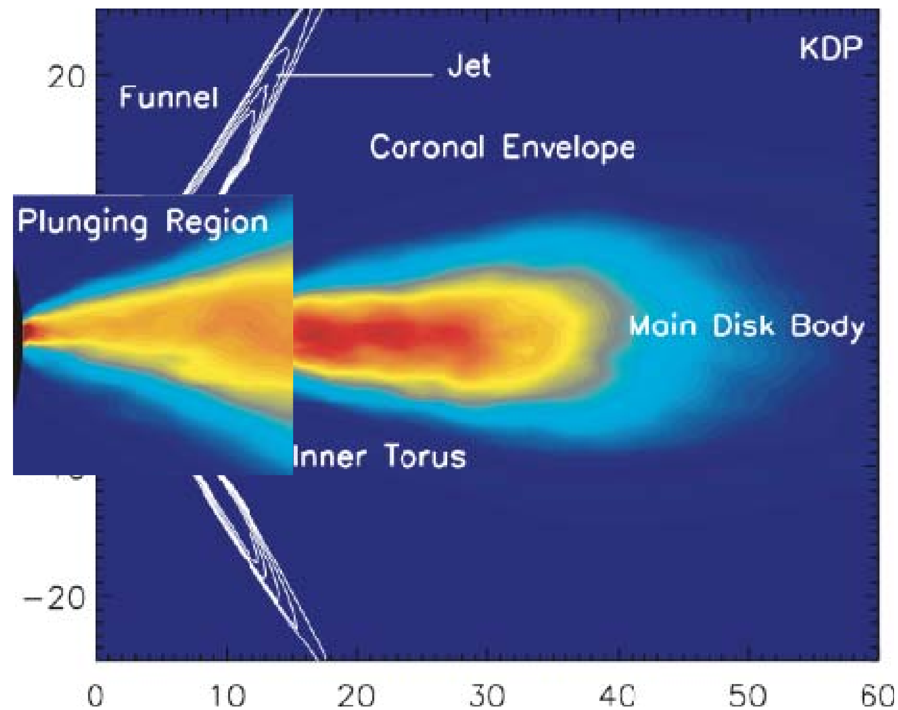
- Global problem difficult to resolve spatially: turbulent scales to parsecs
- Wide range of timescales
- Limited to simple equation of state
- Dissipation, heating, thermodynamics too limited
- Only simple radiative losses; no global radiative transfer
- System scales with M; density set by assumed accretion rate

Approaches to GR MHD Simulations

- GRMHD – De Villiers & Hawley (2003). ZEUS type finite differencing, Boyer-Lindquist coordinates, internal energy equation
- HARM – Gammie, McKinney, Toth, Noble (2003, 2006, 2009). Flux conservative scheme, Kerr-Schild coordinates, total energy equation
- Also, local *shearing box* simulations, done with and without vertical gravity, with both finite difference and flux-conservative schemes

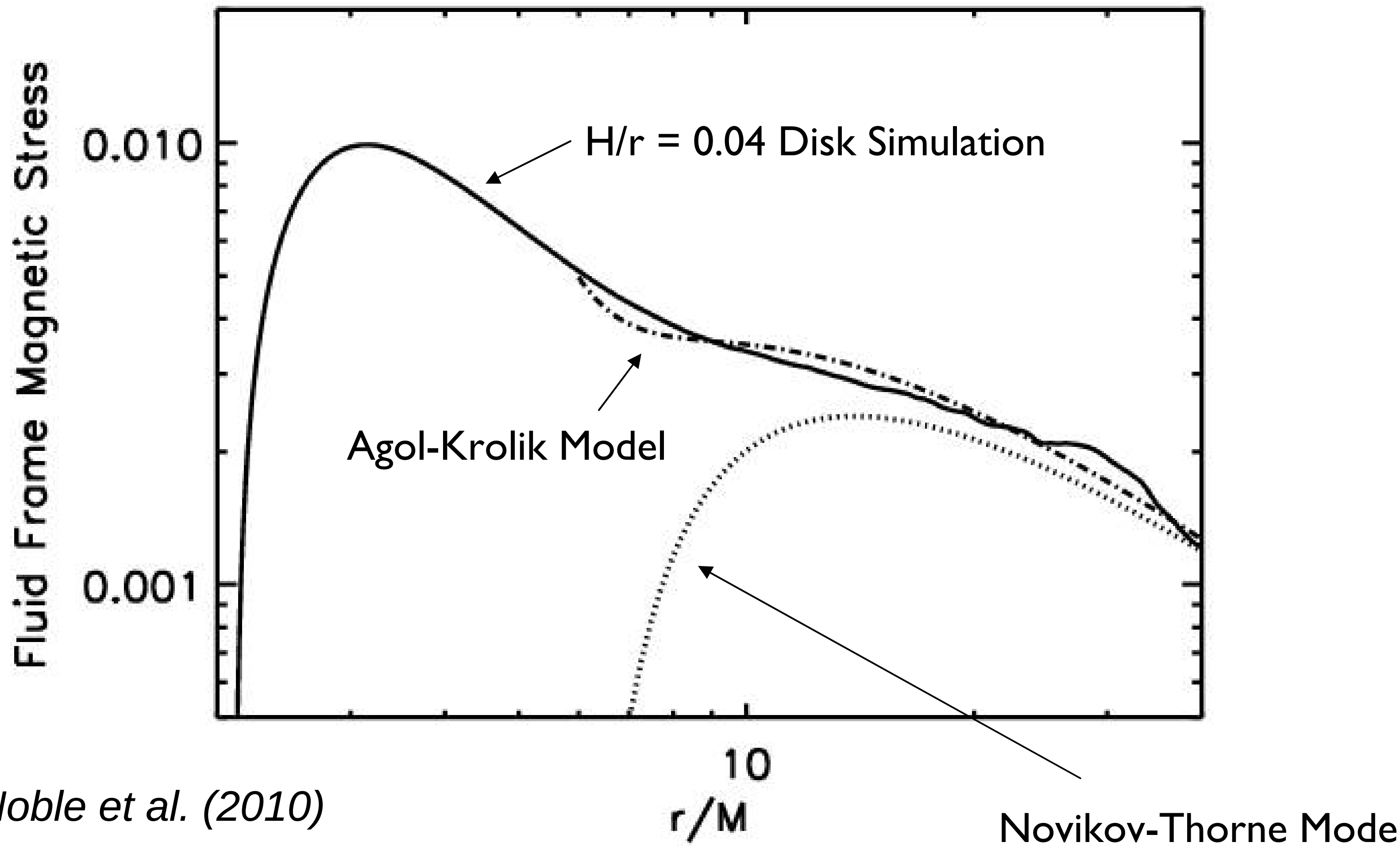
Accretion Disk Simulations: First Results

- Evolution:
  - MRI acts, leading to large-amplitude MHD turbulence, which drives the subsequent matter accretion
- By the End of the simulation:
  - Quasi-steady-state accretion disk, surrounded by a hot corona
  - Black hole axis can be filled with poloidal magnetic field lines
  - Poynting flux jet can be created by the dragging of radial field lines anchored in black hole event horizon by rotation of space time
  - Magnetic stresses at the last stable orbit increase energy release and reduce angular momentum of gas accreted into the black hole



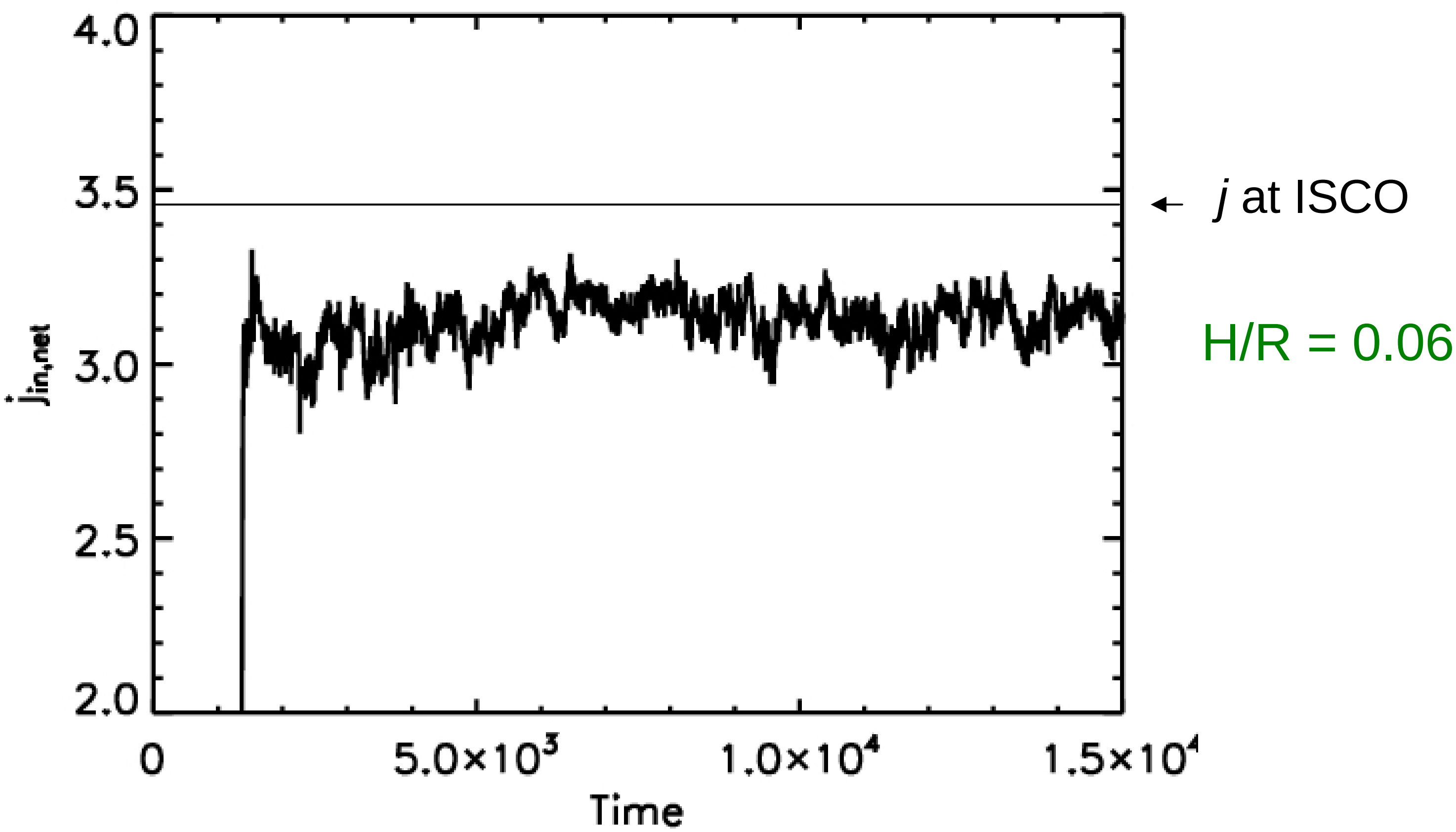
Stress at the ISCO

Fluid Frame Stress, Schwarzschild Hole Simulation



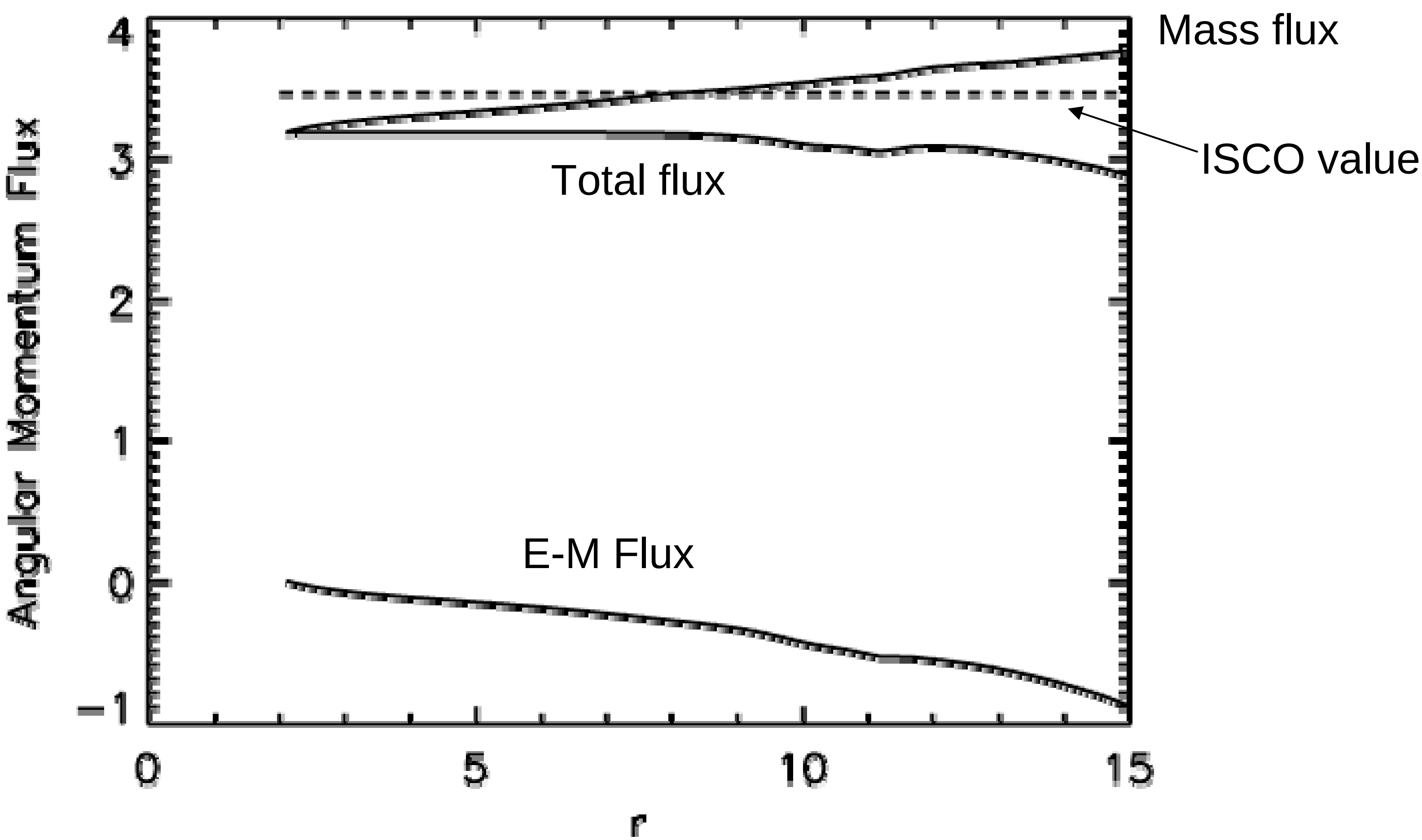
Noble et al. (2010)

Specific Angular Momentum Flux Into Hole



J_{in} = Specific angular momentum accreted into the hole

Specific Angular Momentum Flux, Schwarzschild Simulation



Specific Angular momentum accreted into Schwarzschild Black hole

Simulation	Resolution R,θ,ϕ	Φ domain	H/R	ℓ into hole (ISCO = 3.46)
GRMHD – De Villiers et al 2003	192x192x64	$\pi/2$	0.15	3.25 Down 7%
GRMHD – Hawley & Krolik 2006	192x192x64	$\pi/2$	0.15	3.13 Down 10%
GRMHD Schnittman et al 2006	192x192x256	2π	0.15	3.09 Down 11%
HARM3d Shafee et al 2008	512x128x32	$\pi/4$	0.07	3.36 Down 3%
HARM3d Noble	192x192x64	$\pi/2$	0.05	3.1 Down 11%
HARM3d Noble	512x160x64	$\pi/2$	0.05	3.15 Down 9%

Role of H/R: Systematic Study Is In Order

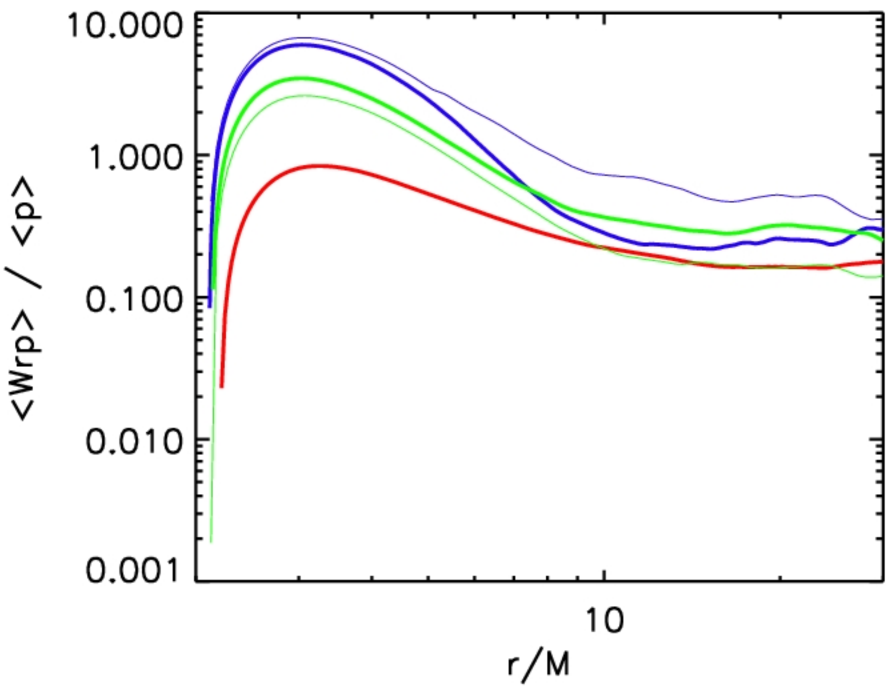
- Noble et al (2010): Run a series of disks with same initial conditions but cooled to different H/R
- Scale height control achieved by cooling to a target temperature
- Scale height defined as the density moment in the coordinate frame
- Scale height targets: H/R = 0.16, 0.08, 0.05, two different initial tori with high and medium resolution
- Initial field consists of dipole loops, $\beta = 100$

Results

Resolution	Target H/R	Actual H/R	J net	Zones within H of equator
912x160x64	0.05	0.061	3.13 Down 10%	81
192x192x64	0.05	0.085	3.07 Down 11%	60
512x160x64	0.08	0.10	3.08 Down 11%	103
192x192x64	0.08	0.091	3.10 Down 11%	35
348x160x64	0.16	0.17	2.93 Down 15%	74

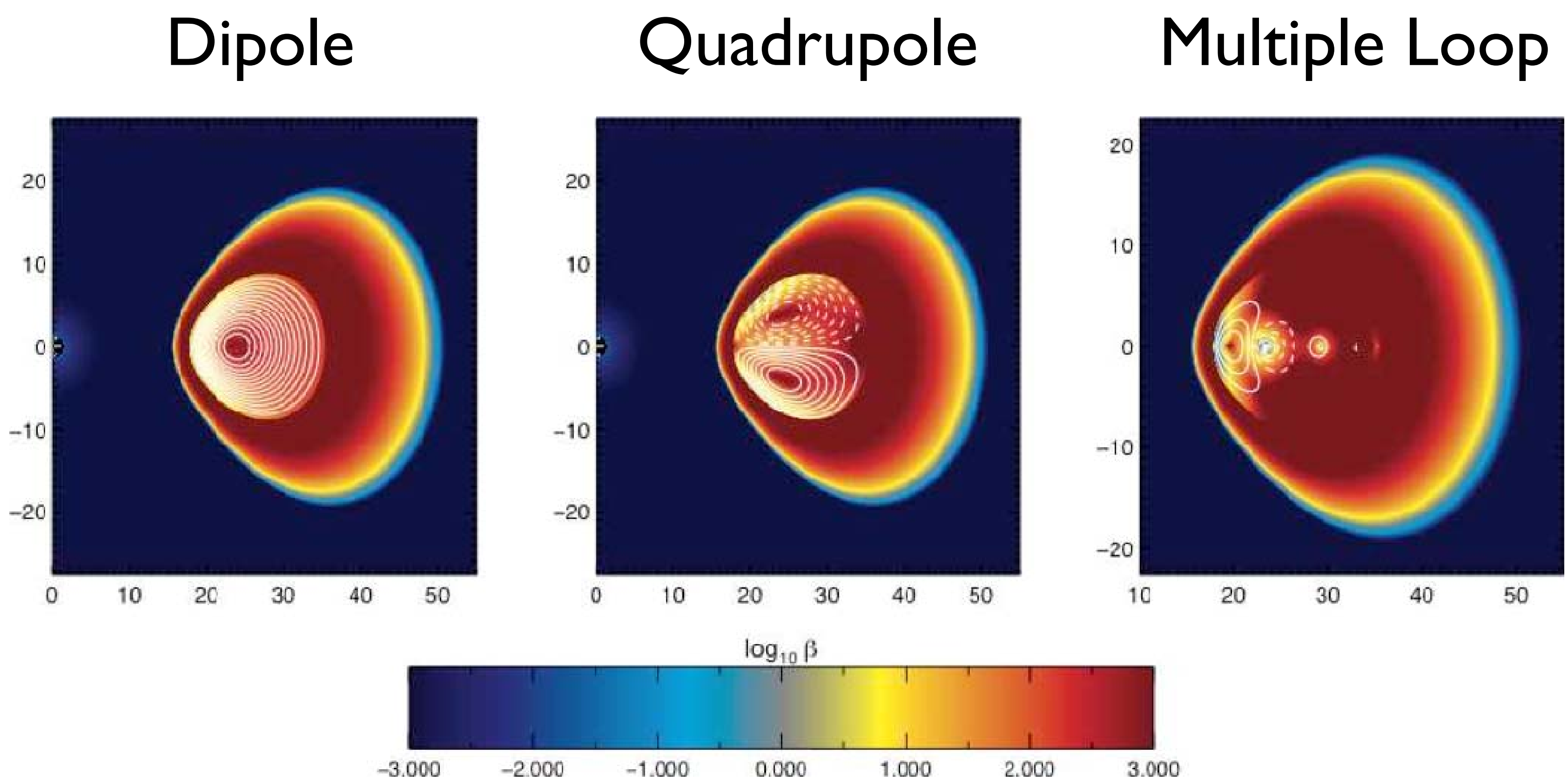
Stress in terms of α

- Nominal α values in disk ~0.2-0.5
- In plunging region α values are large– thinnest disks have the largest value
- EM stress independent of pressure; α not meaningful inside and near ISCO
- (See also results on α from radiative shearing box simulations)



Blue: H/R = 0.05
Green: H/R = 0.08
Red: H/R = 0.16

Effect due to Initial Field Topologies?



+ net vertical and toroidal only

GRMHD Simulations with different Topologies

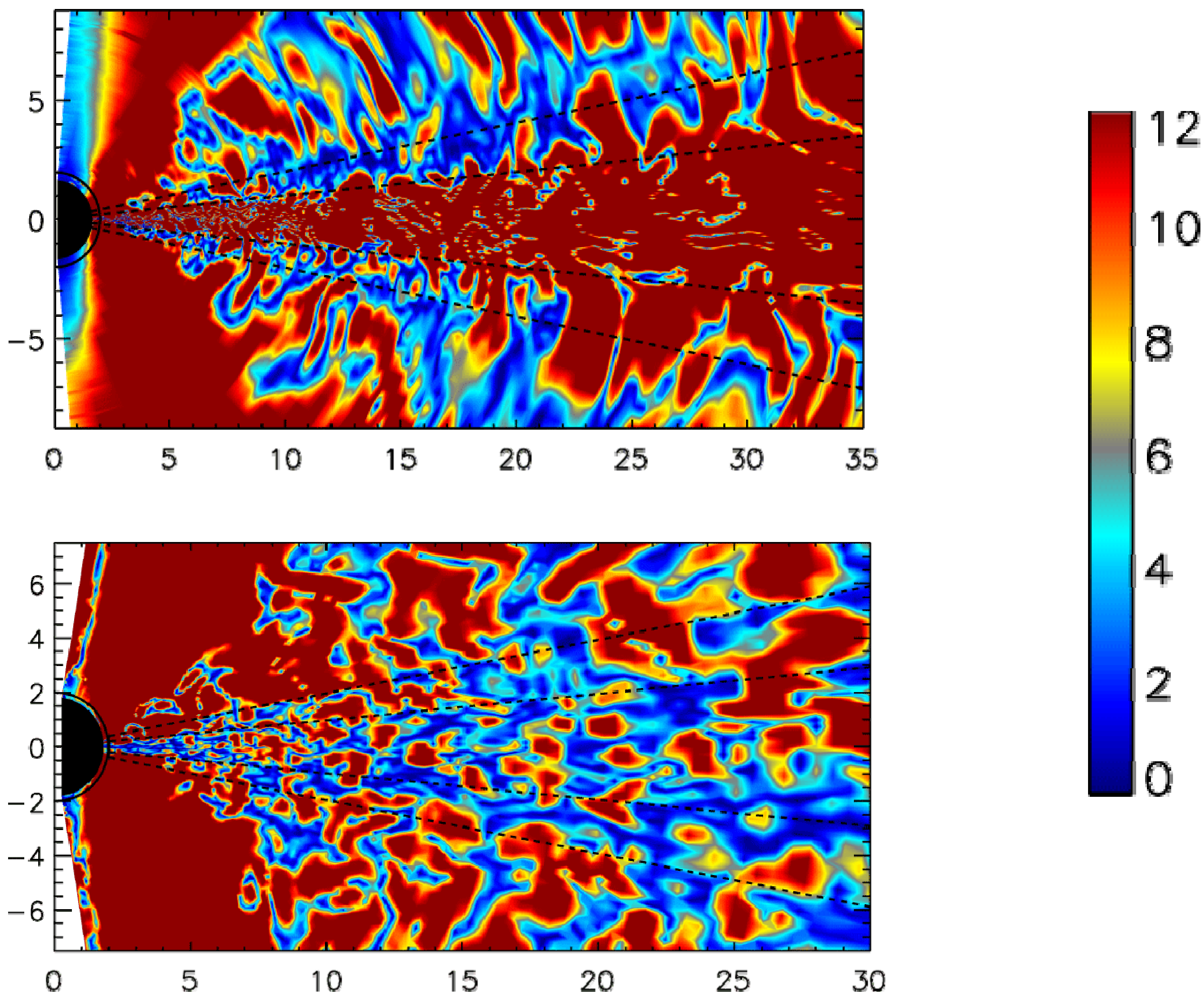
- No cooling – typical thickness H/R ~ 0.14
- Vertical field gives largest stress
- Quadrupolar and Dipolar fields similar
- No significant reduction in *j* for toroidal field case

Topology	Spin	J net
Vertical	0.	Down 12%
Dipole	0.	Down 7%
Quadrupole	0.	Down 7%
Dipole	0.9	Down 5%
Quadrupole	0.9	Down 5%
Toroidal	0.9	ISCO value

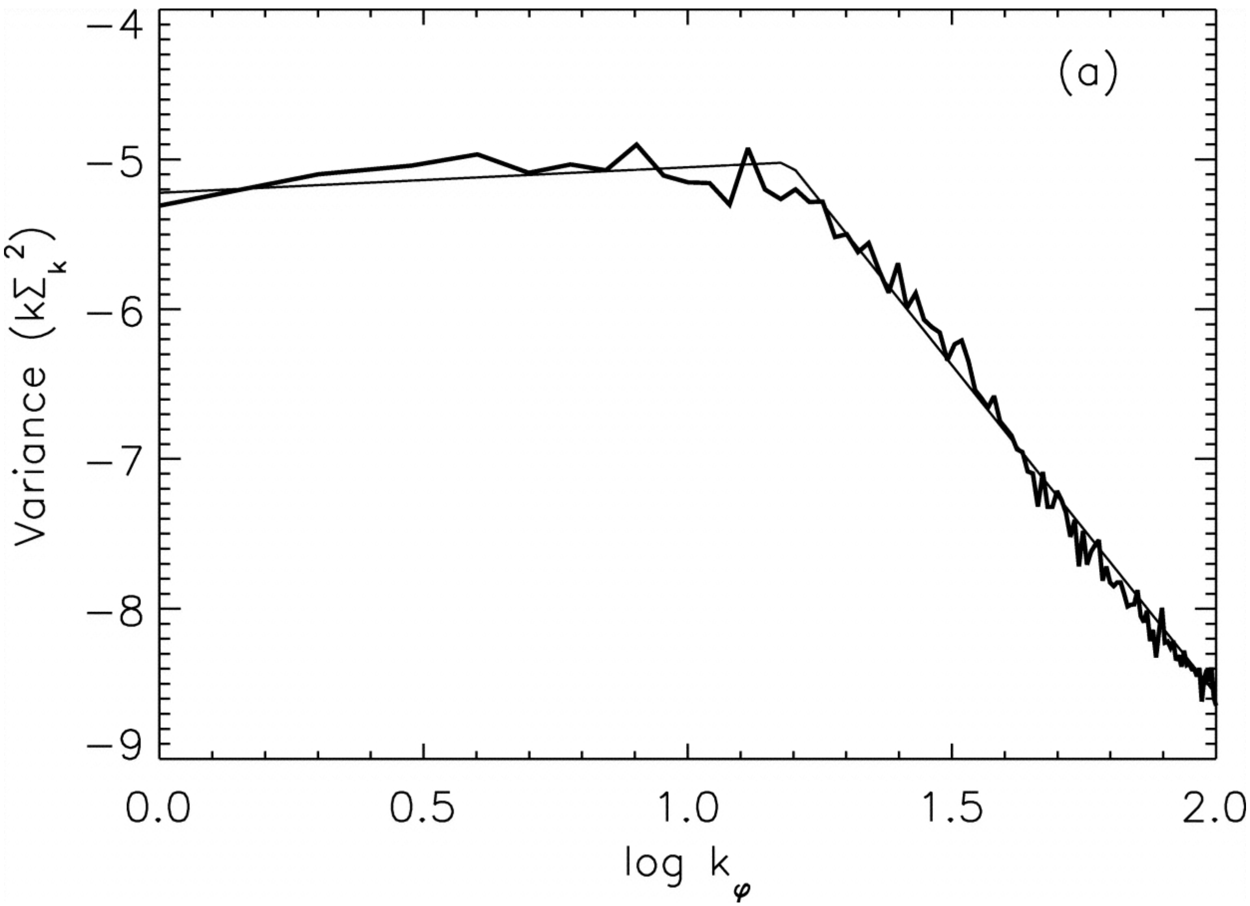
Importance of Resolution: Grid zones per MRI Wavelength

H/R=0.1 High Res

H/R=0.1 Low Res
Late time



Azimuthal Fluctuations



Schnittman, Krolik & Hawley (2006)

Empirical Inferences

- Must take care with resolution, inflow equilibrium, etc.
- Azimuthal extent of simulation may also matter
- Magnetic geometry matters

  (Vertical field vs. zero net-flux vs. toroidal field)
- Reynolds stress shows a dependence on H/R
- Magnetic effects do increase with H/R, but slowly

Summary: Stress at the ISCO

- Magnetic stress can operate at and inside the ISCO
- Amount of additional stress depends on field strength and topology near ISCO
- Disk thickness H/R seems less important
- Black hole spin can influence the accretion disk directly through magnetic torques
- Magnetic stress near or inside the ISCO can affect efficiency and has implications for inferring spin from observations
- Magnetic torques may limit *a*/*M* value for holes spun up by accretion
- *The black holes appearing in the films are fictitious. Any resemblance to actual black holes, spinning or dead, would be most welcome*