Global Simulations of Black Hole Accretion and Jets

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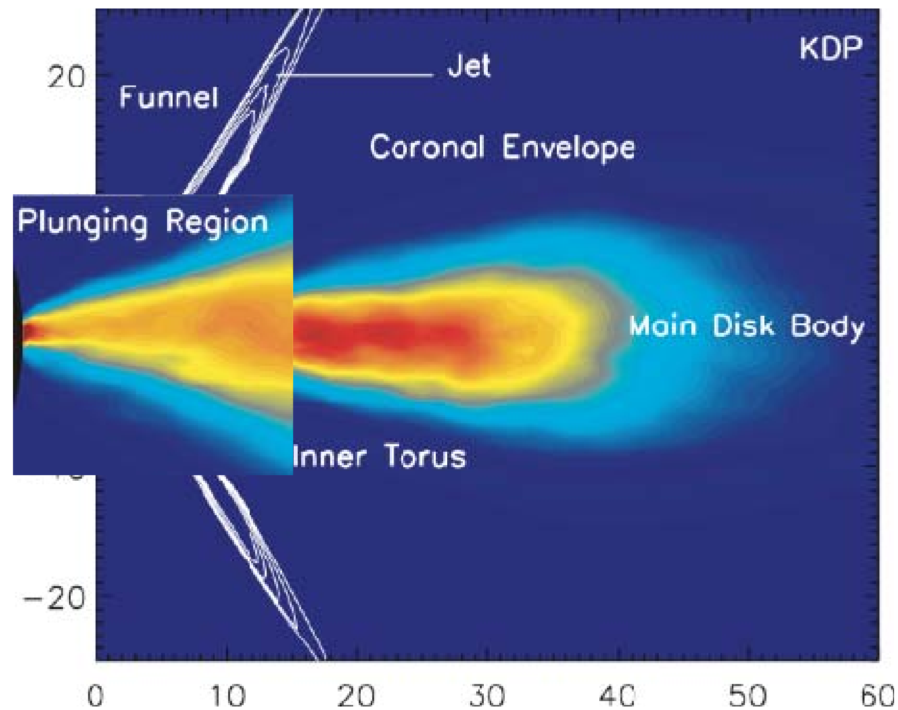
Current Global Simulations

- 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

Accretion Disk Simulations

- Evolution:
  - Magnetic instabilty 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 filled with rotating magnetic field lines
  - Energy flux in jet due to 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

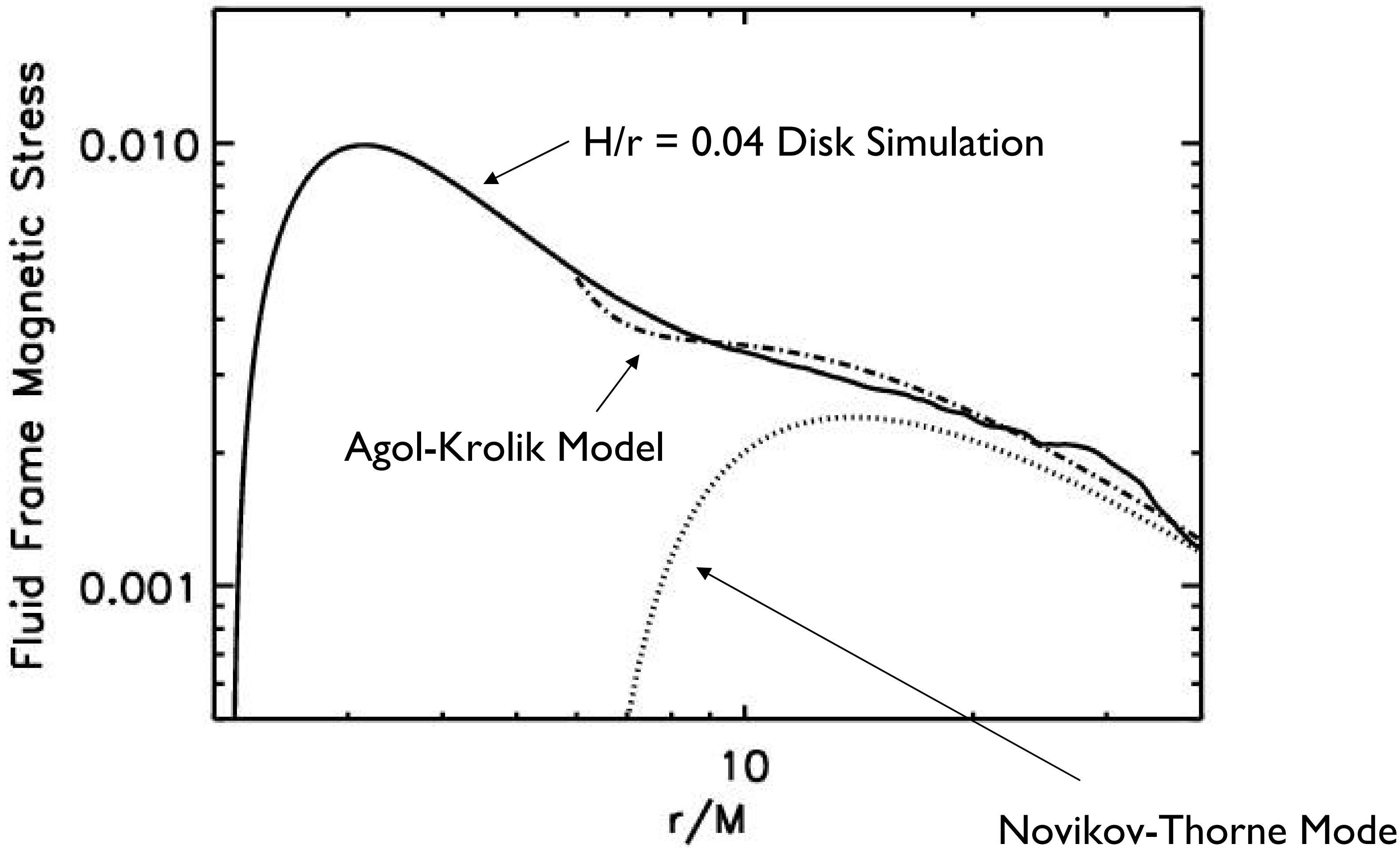


MHD Stress at the ISCO

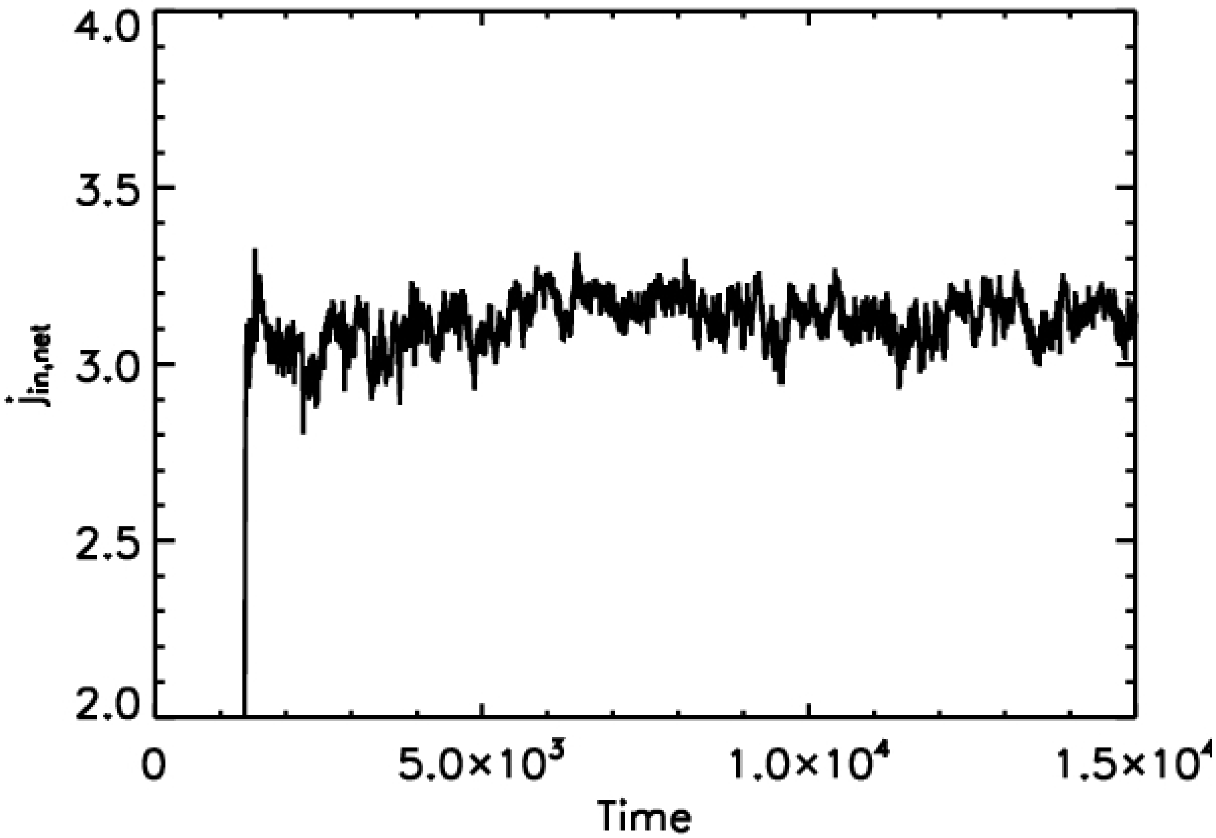
New Features: MHD Stress at the ISCO

- Total disk luminosity depends on how much angular momentum can be removed from the accreted gas
- Conventional disk theory (Shakura-Sunyaev, Novikov-Thorne) assumes stress goes to zero at the Innermost Stable Circular Orbit (ISCO)
- 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?

Fluid Frame Stress, Schwarzschild Hole Simulation



Angular Momentum Flux Equilibrium



H/R = 0.06

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

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
GRMHD – Hawley & Krolik 2006	192x192x64	$\pi/2$	0.15	3.13
GRMHD Schnittman et al 2006	192x192x256	2π	0.15	3.09
HARM3d Shafee et al 2008	512x128x32	$\pi/4$	0.07	3.36
HARM3d Noble et al. 2009	192x192x64	$\pi/2$	0.05	3.1
HARM3d Noble et al. 2009	512x160x64	$\pi/2$	0.05	3.15

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

Empirical Inferences

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

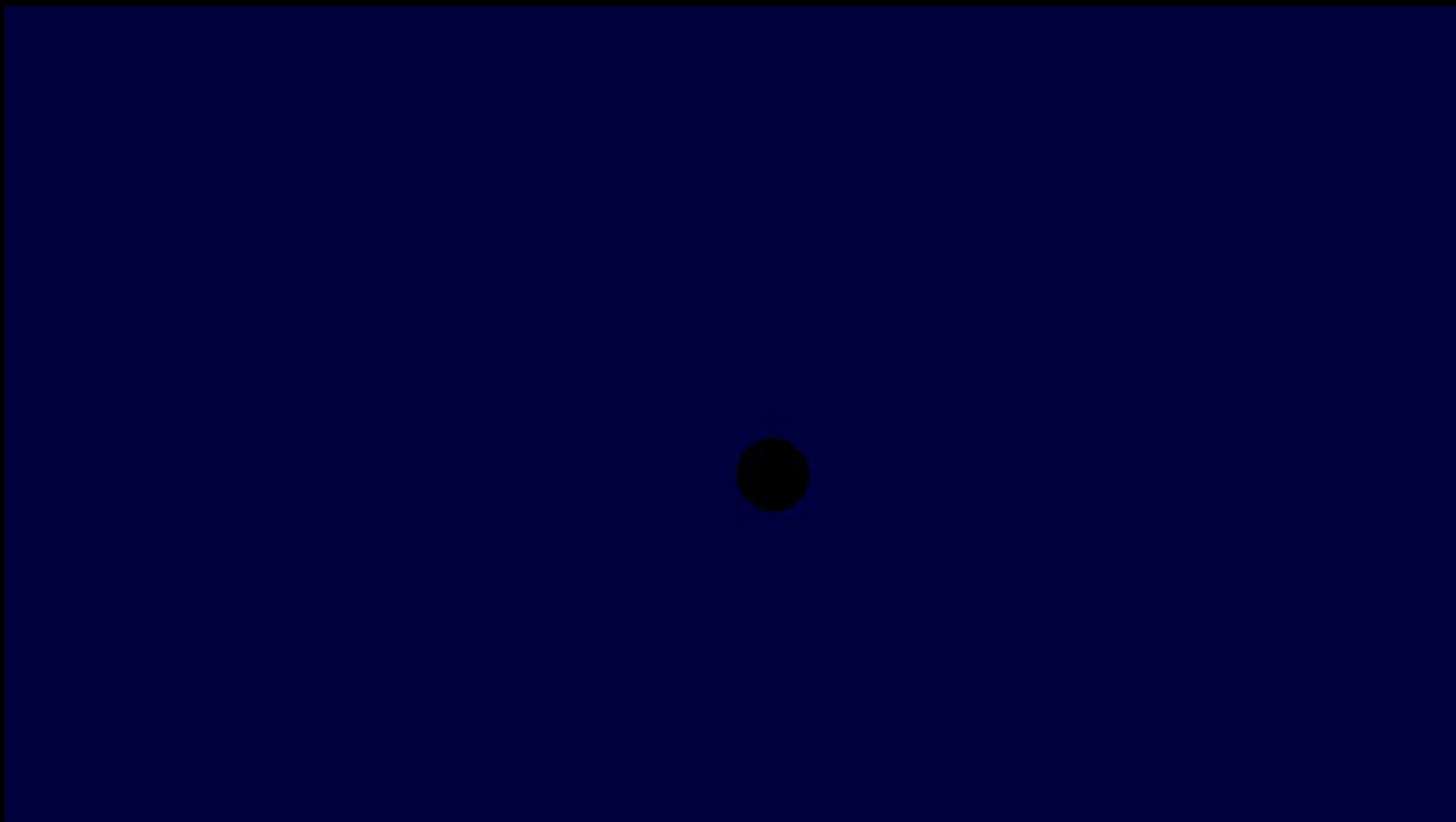
  (Vertical field vs. zero net-flux vs. toroidal field)
- Magnetic effects do increase with H/R, but slowly

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

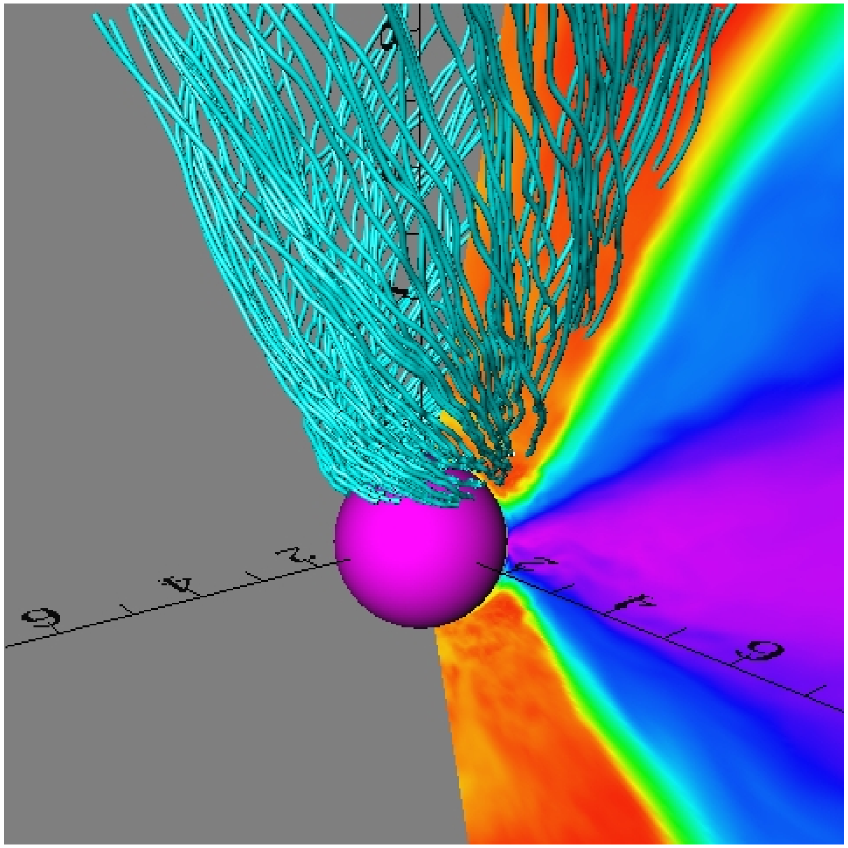
Poynting Flux Jets

Formation of Poynting Flux Jet



Simulation Results: Jets

- Outflow throughout funnel, but only at funnel wall is there significant mass flux
- Outgoing velocity ~0.4 - 0.6 c in funnel wall jet
- Poynting flux dominates within funnel
- Both pressure and Lorentz forces important for acceleration
- Existence of funnel jet depends on establishing radial funnel field
- Jet luminosity increases with hole spin – Poynting flux jet is powered by the black hole



Substantial Jet Energy Efficiency for Rapid Spin

a/M		η_{EM}	η_{NT}
-0.9		0.023	0.039
0.0		0.0003	0.057
0.5		0.0063	0.081
0.9		0.046	0.16
0.93		0.038	0.17
0.95		0.072	0.10
0.99		0.21	0.26

Hawley & Krolik 2006

Field Topology

- Properties of magnetized black hole accretion disks seem to be remarkably insensitive to magnetic field topology: the only dependence is in terms of the magnetic field strength. Appearance of disk should be independent of magnetic field topology

- This is not true for the jet:

  – Jet formation requires a consistent sense of vertical field to brought down to the event horizon

  – This occurs readily for dipole, less so for quadrupole, not at all for toroidal initial field topologies

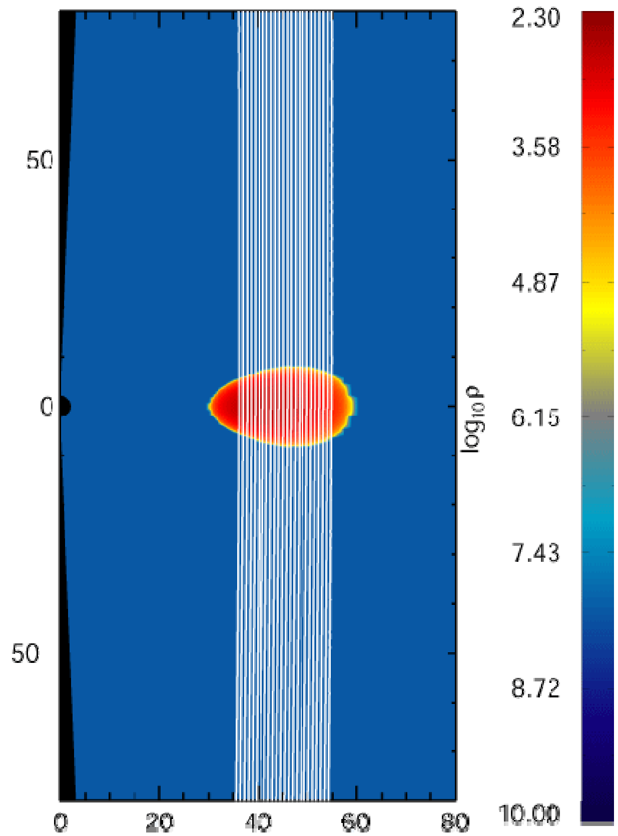
  – Reconnection events between funnel and disk field determine the variability of the jet

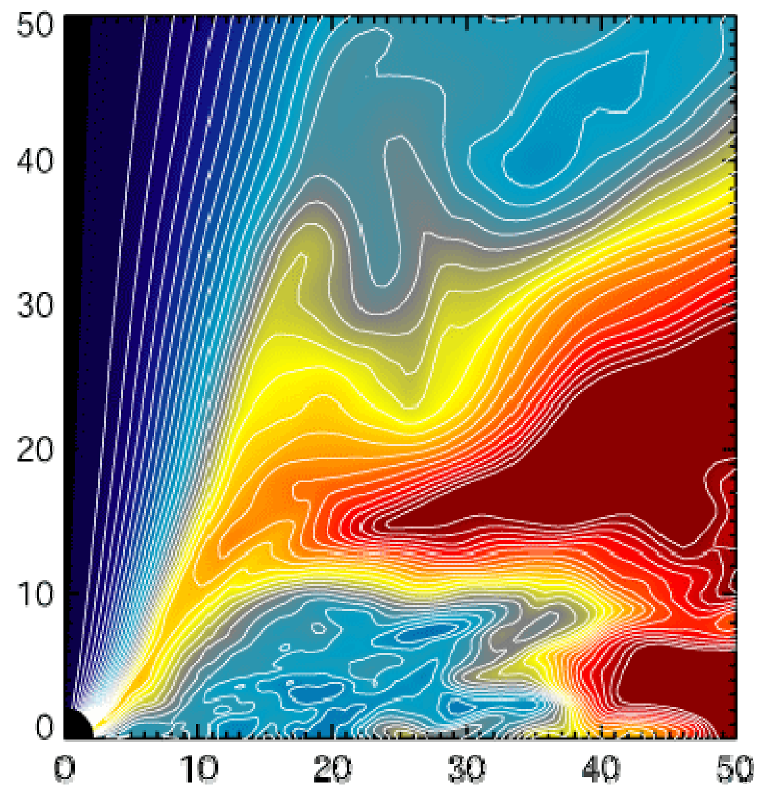
Origin of Large Scale Jet Field

- Is net vertical flux required, or just large-scale poloidal field?
  - In simulations, strong jets only form when dipole is brought down to the hole
- Can significant large-scale poloidal field be generated solely by the MRI within turbulent disks?
  - In simulations some coherent initial poloidal field has been required
- How does the presence or absence of a jet relate to the overall state of the disk and its magnetic field?
  - Funnel field (and jet) strength related to total pressure in near-hole disk
  - Initial collimation provided by disk and corona pressure

Radial Advection of Net Vertical Field

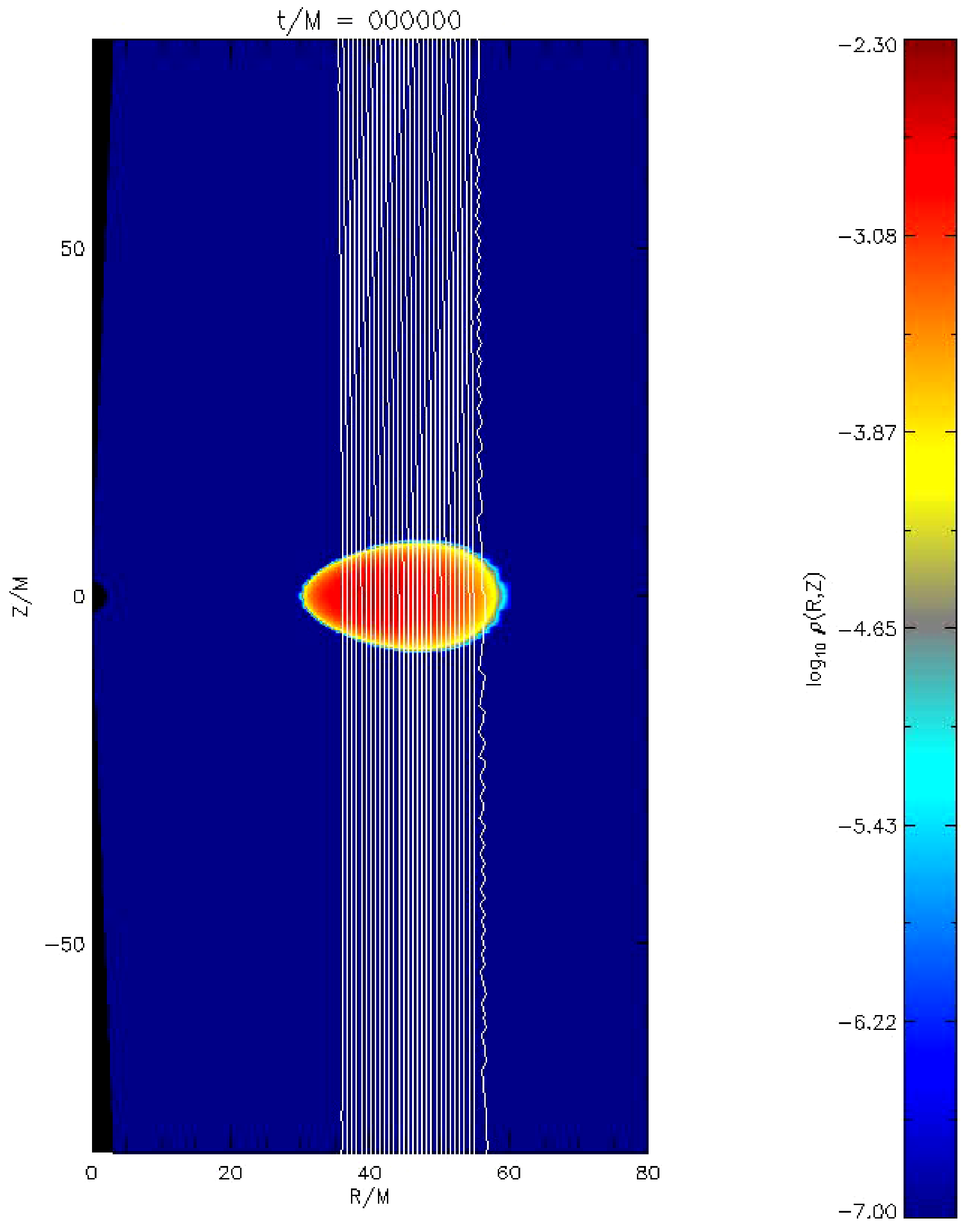
Advection of vertical field by Accretion flow



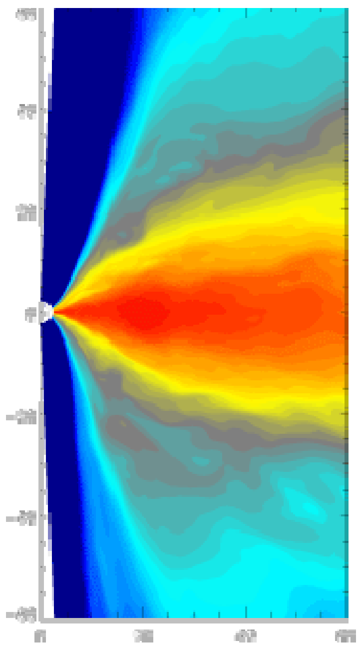


- Can net field be advected inward by MRI turbulent disks? Balance magnetic diffusion/reconnection timescale against accretion timescale?
  - Flux diffusion in the disk can occur but coronal processes seem more efficient at bringing field to the hole

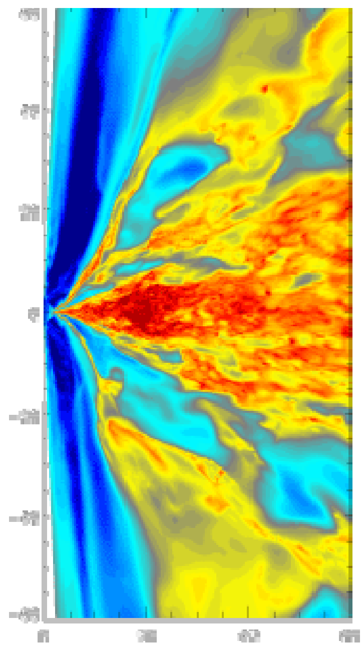
Beckwith et al 2009


t/M = 000000
Z/M
50
0
−50
0
20
40
60
80
R/M
−2.30
−3.08
−3.87
−4.65
−5.43
−6.22
−7.00
log10 ρ(R,Z)

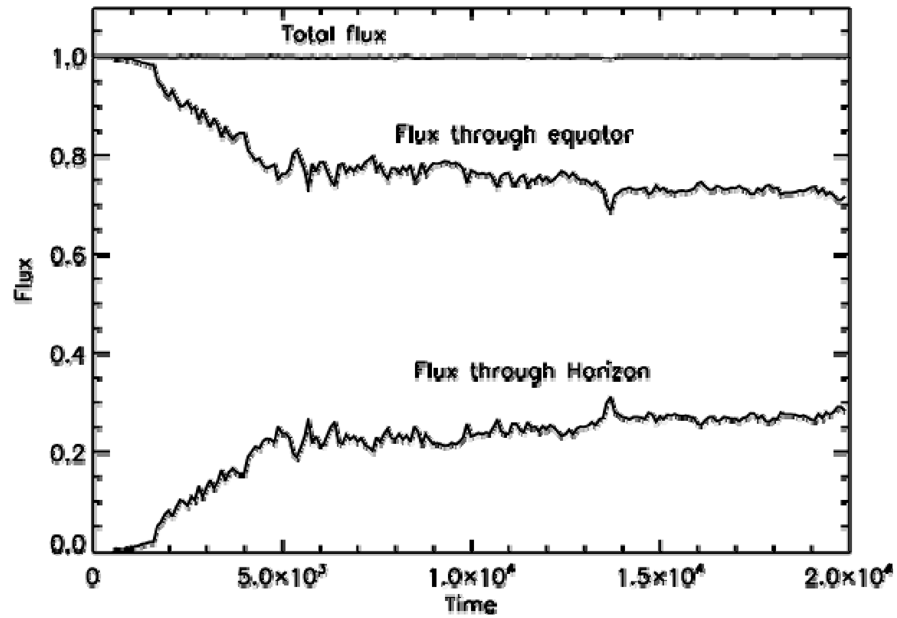
Accumulation of Net Flux



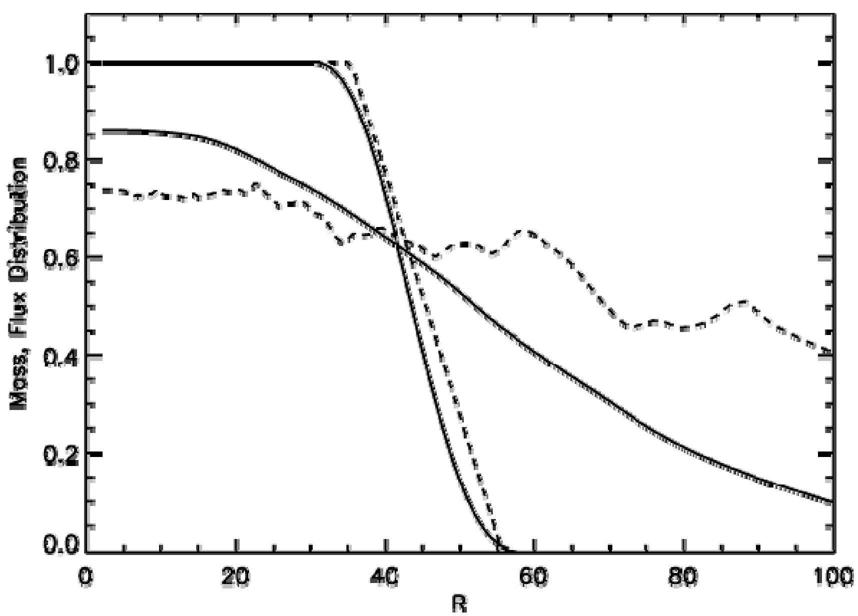
Density



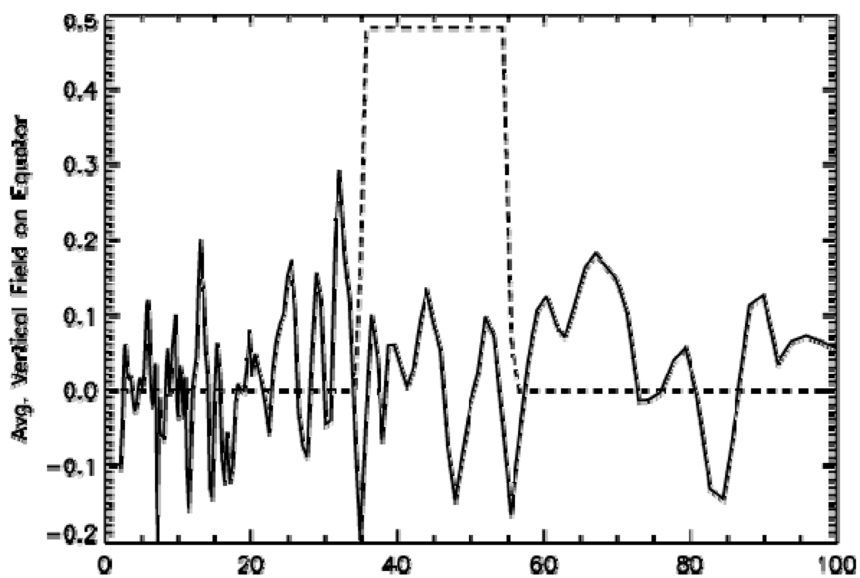
β Parameter



Net Flux, Mass, Vertical Flux in Disk



Initial and late time matter and Net flux distribution



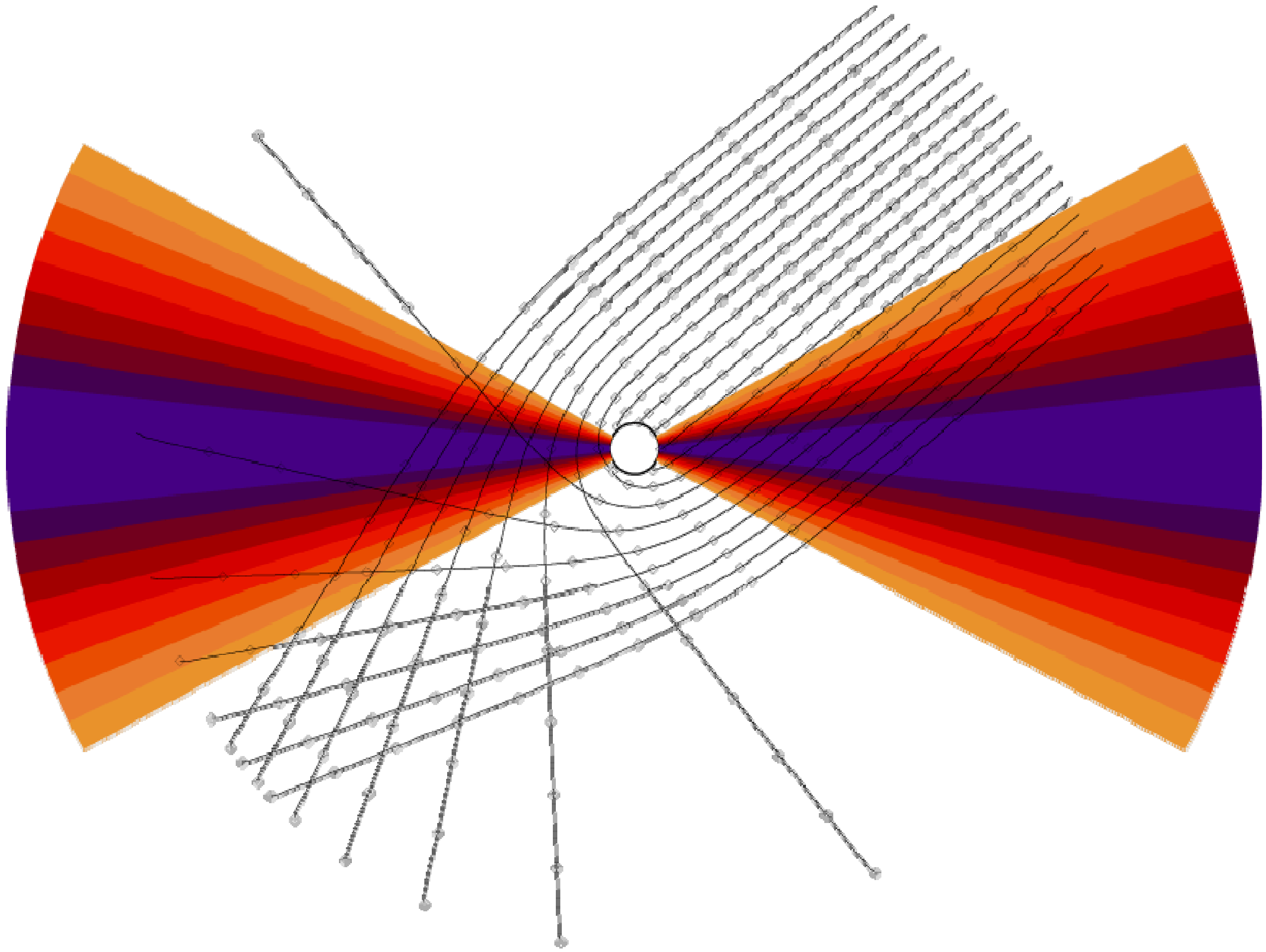
Vertical flux through Equator Late time

Transport of Net Flux

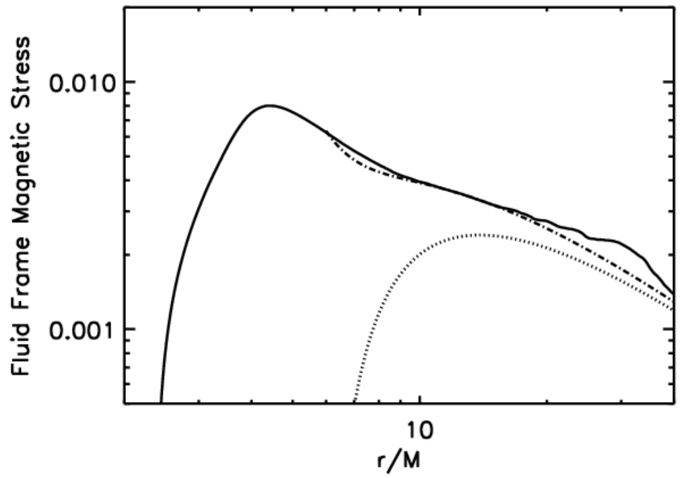
- *Global* processes can dominate over local processes
- See Spruit & Uzdensky (2005); Rothstein & Lovelace (2008)
- Within the turbulent disk (and in turbulent shearing box simulations) net flux can “diffuse”
- MRI turbulence (“alpha viscosity”) effective at transporting angular momentum and mass; rapid reconnection prevents effective transport of net flux
- “Turbulent magnetic Prandtl number” description not useful

First Steps Toward Observational Implications

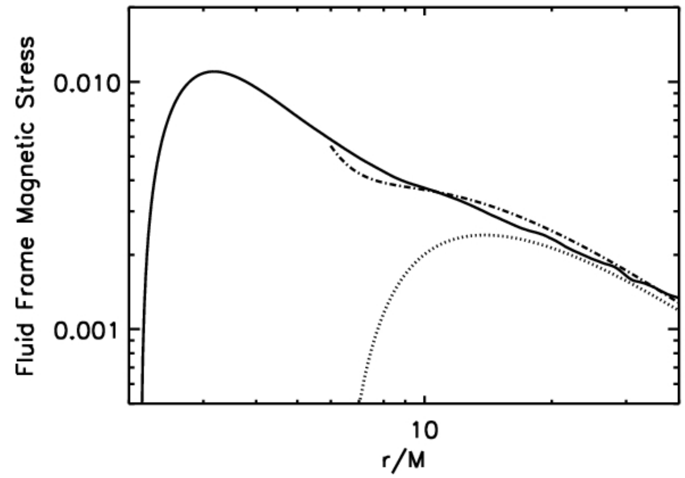
Observable Properties: Ray Tracing in the Kerr Metric



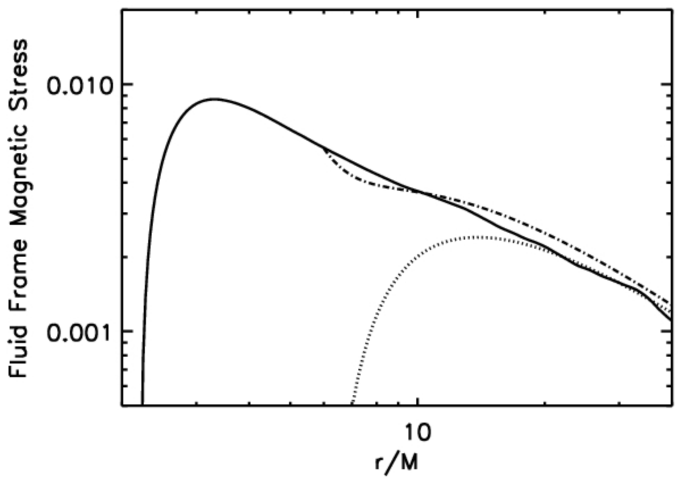
Fluid-Frame Stress Profiles



H/R=0.06

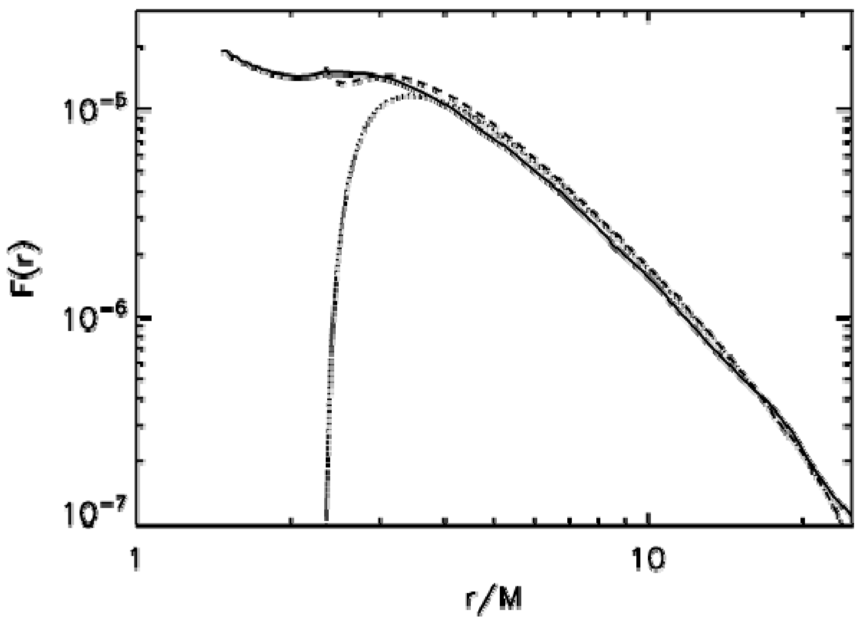


H/R=0.10

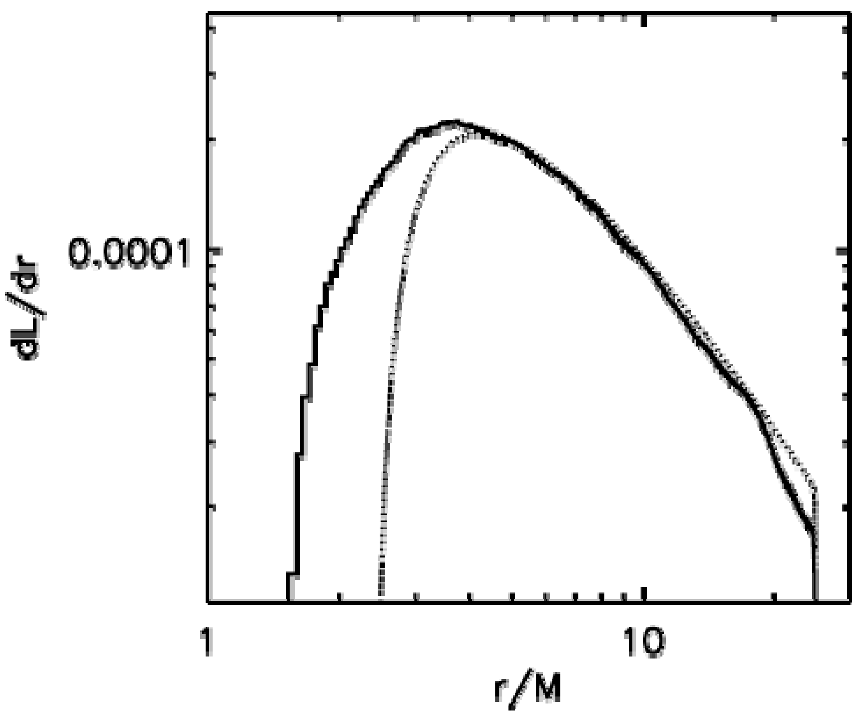


H/R=0.17

Enhanced Luminosity from Enhanced Stress



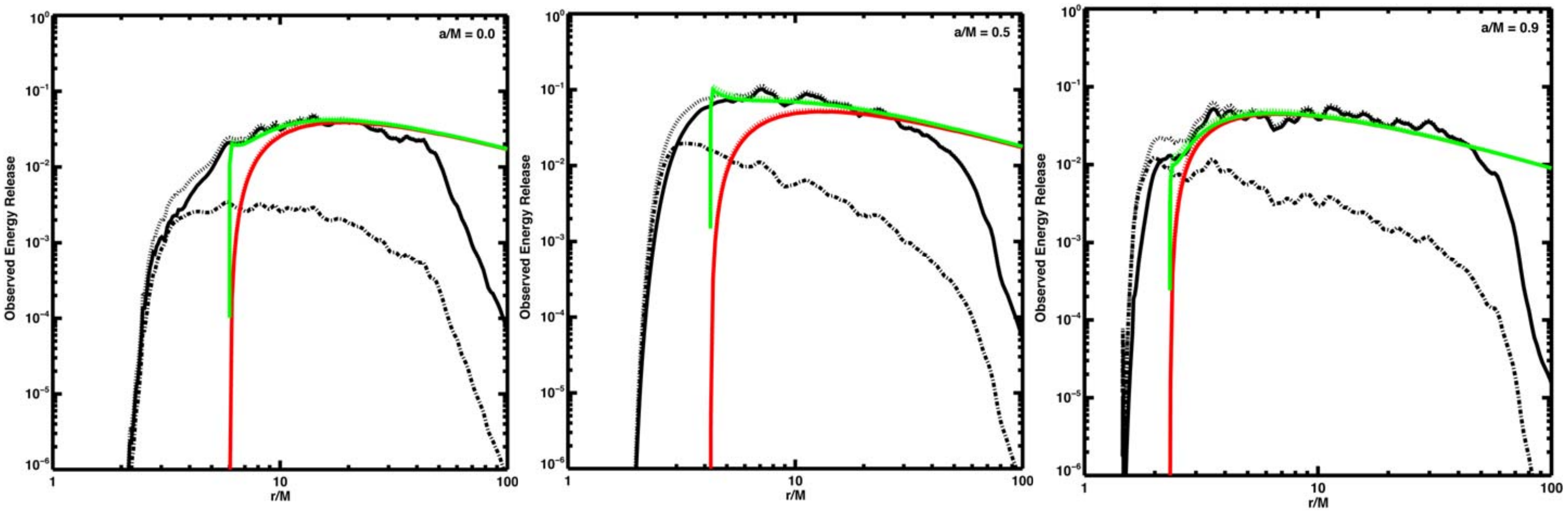
Radiated Flux per unit area



Luminosity received at infinity per unit radial coordinate

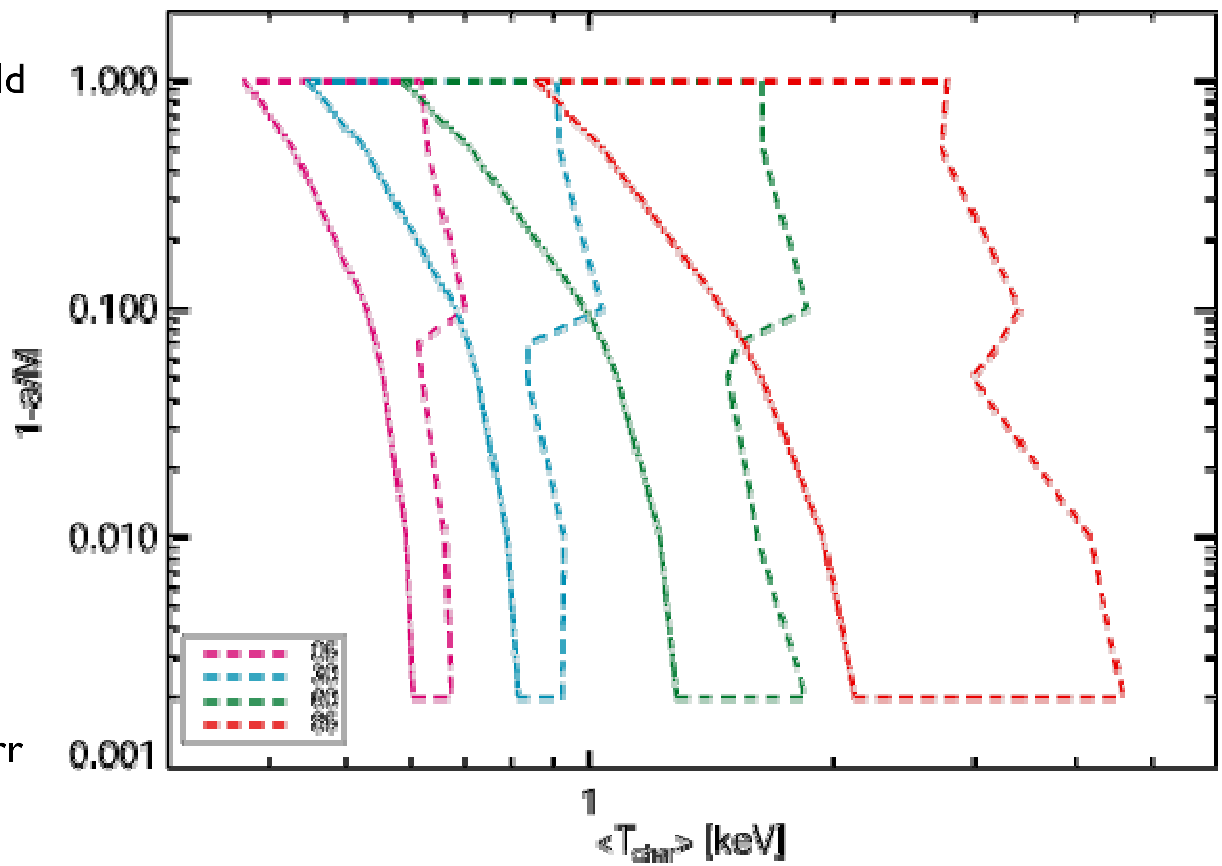
Noble et al (2009)

But What Fraction of the Photons Escape---
and With What Doppler Shift?



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

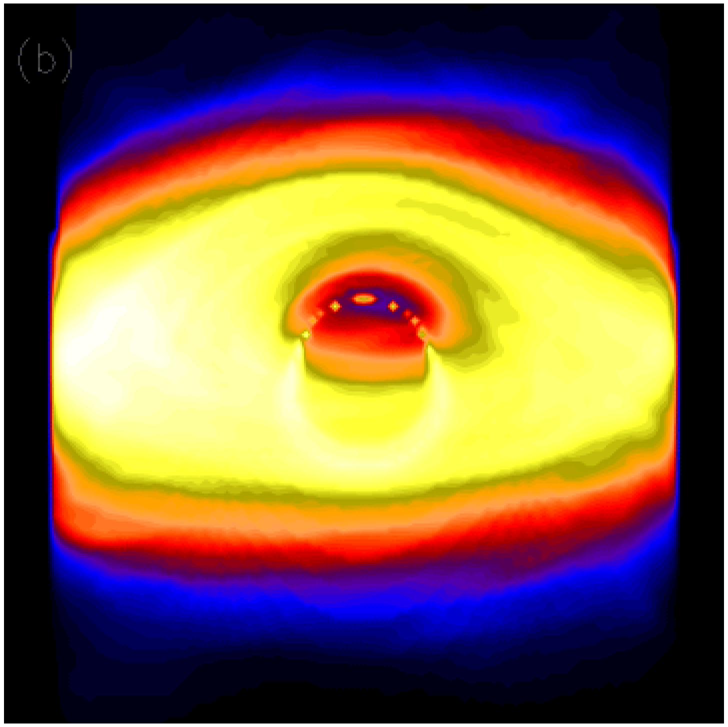
Schwarzschild



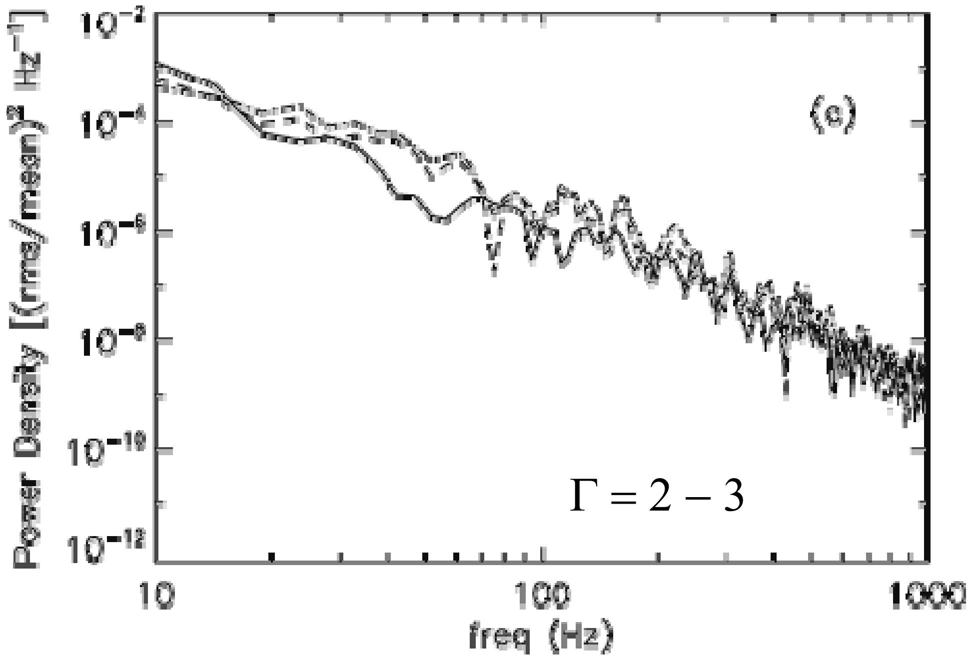
Maximal Kerr

Beckwith et al 2008

Simulated emission



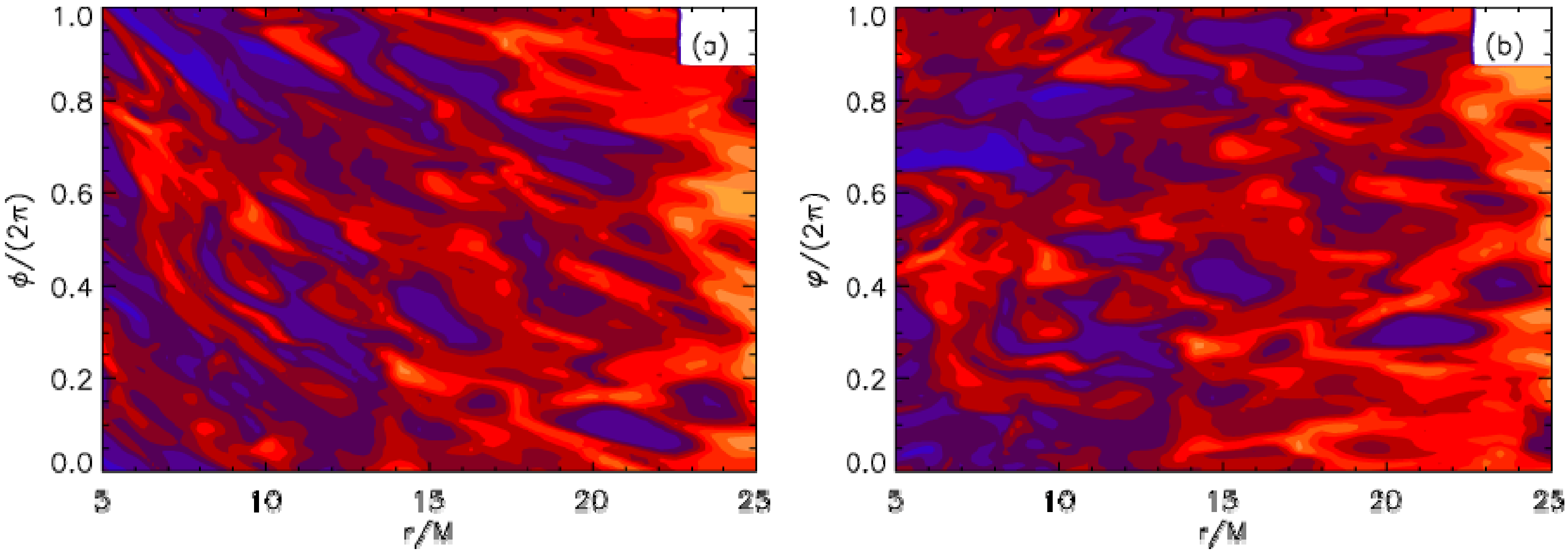
Optically thin line emission
Inclination angle 70 degrees



Power spectrum from simulated light curve

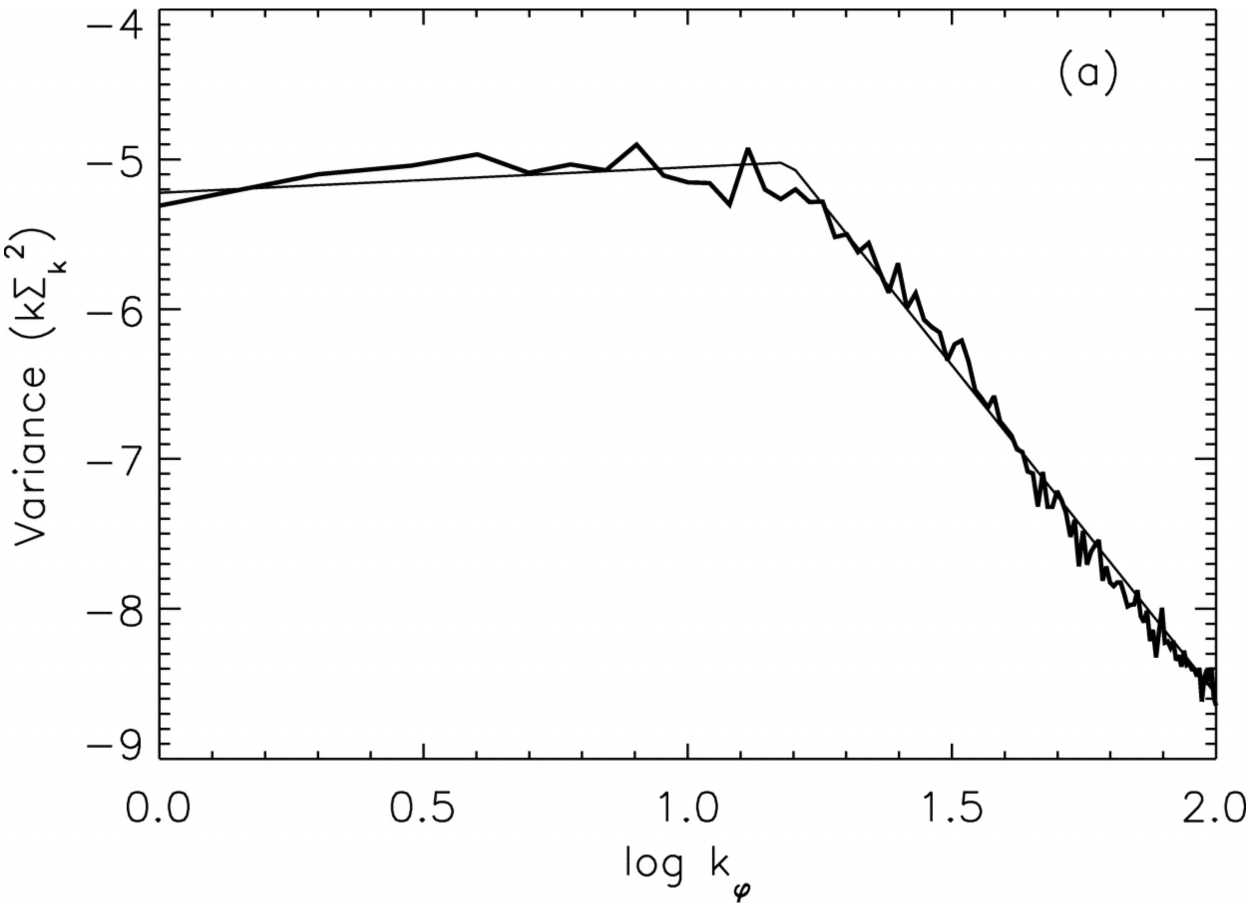
From Schnittman, Krolik & Hawley 2006, ApJ, 651, 1031

Hot Spots in the Disk



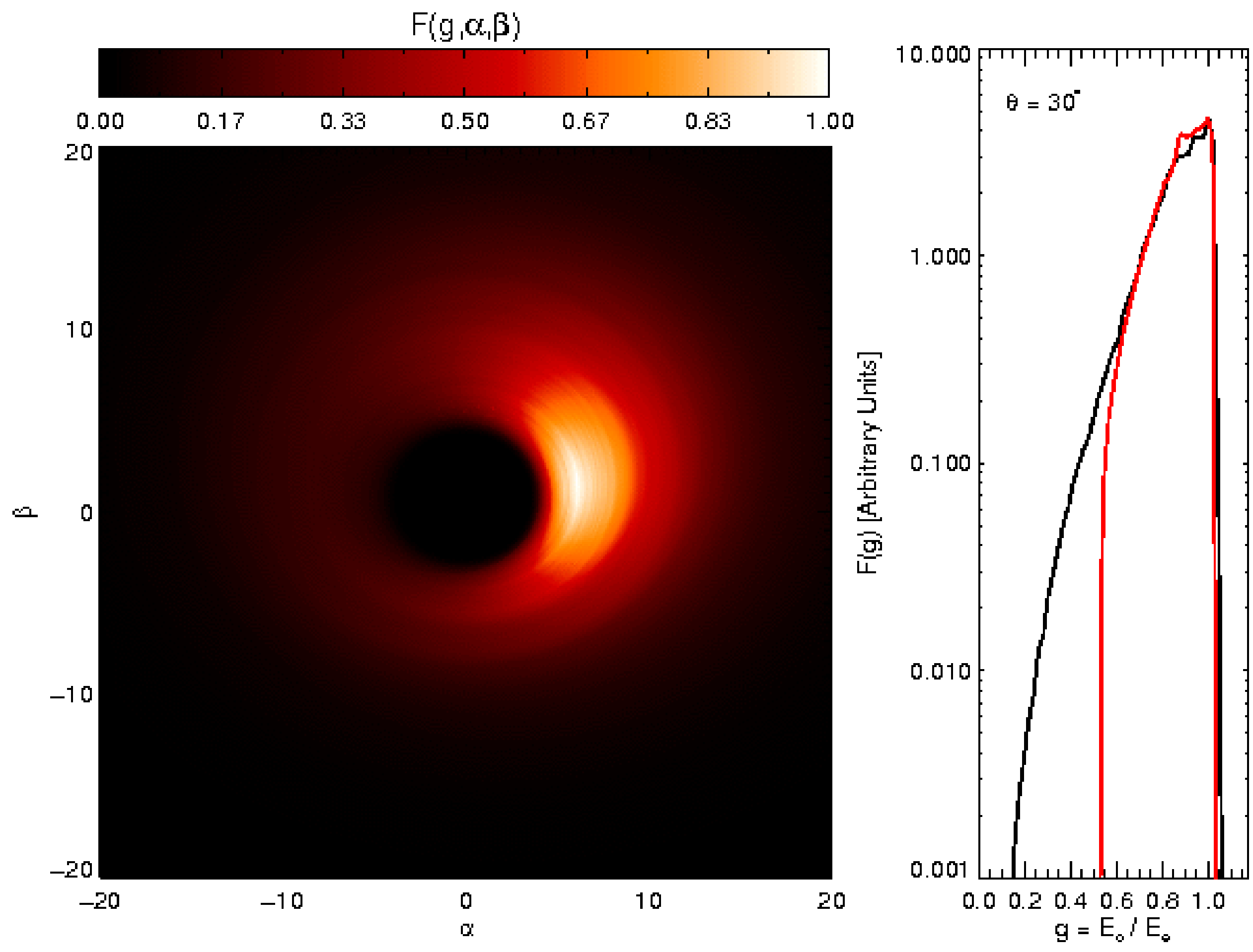
Surface density perturbations at one moment in time

Azimuthal Fluctuations



Schnittman, Krolik & Hawley (2006)

Simulated Fe Kα Line



Variability in BH Systems: 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

Effect of Accretion on Black Hole Spin Evolution

Accreted Angular Momentum

- Internal torque in excess of the Novikov-Thorne level can reduce specific angular momentum of accreted matter below ISCO value (no stress edge)
- Torque from spinning hole extracts angular momentum
- Jet carries away some angular momentum – hole absorbs EM flux with negative spin
- Result is spin down for some 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

Summary

- The MRI leads to MHD turbulence that transports angular momentum, allowing disks to accrete
  - Stress determines the pressure, not the other way around. It is still uncertain what determines turbulent field strengths
- Poynting flux jet power comes from black hole spin
  - Under what circumstances does required axial field become established?
- Magnetic stress can be significant near or inside the ISCO
  - Additional stress can be present, but additional work needed to understand how much and when
  - Need better models to relate stress to emission in simulations
  - Increase stress leads to larger characteristic disk temperatures, greater efficiency compared to standard NT model
- Magnetic torques may limit a/M value for holes spun up by accretion