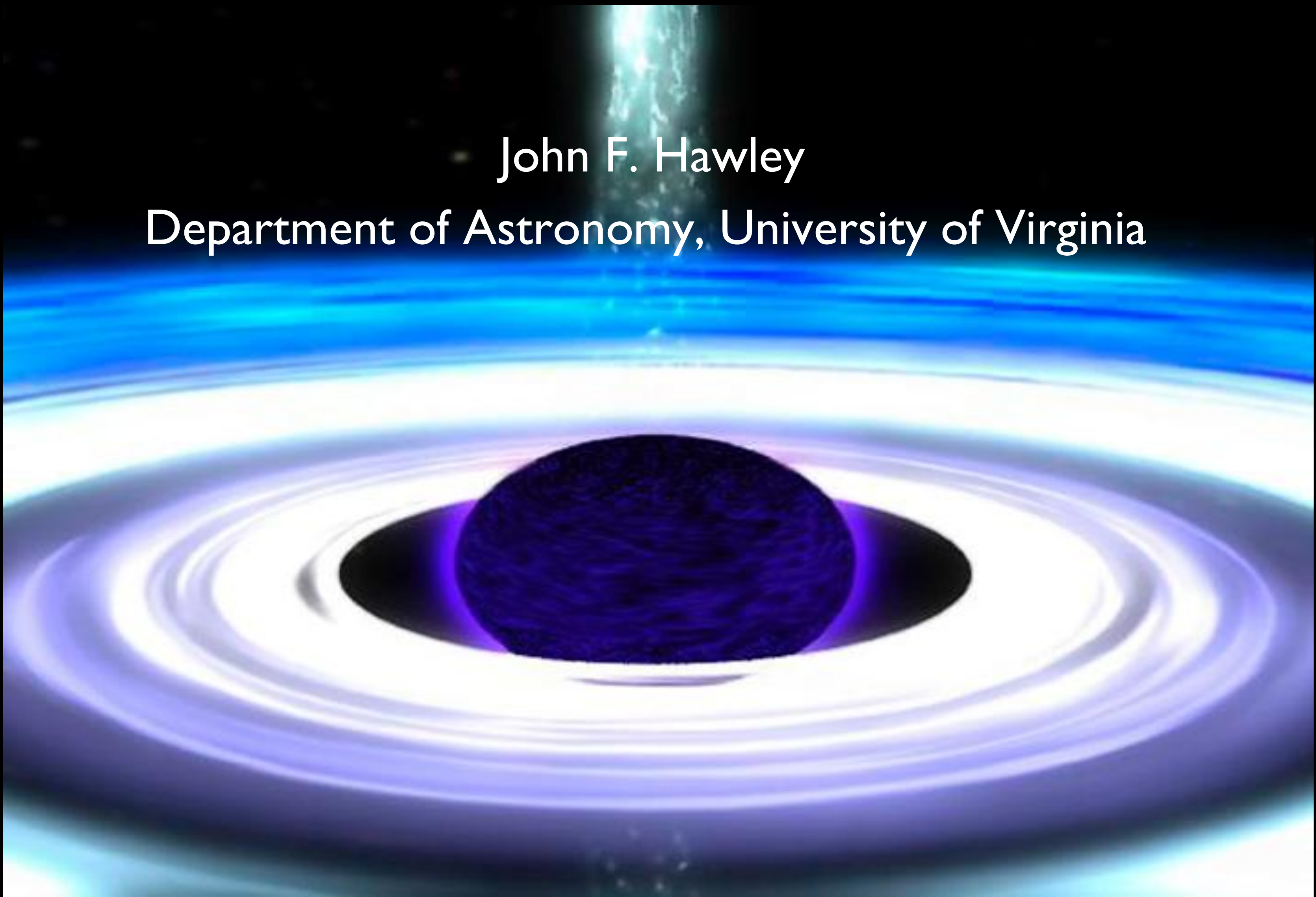
Global Simulations of Black Hole Accretion



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Collaborators and Acknowledgements

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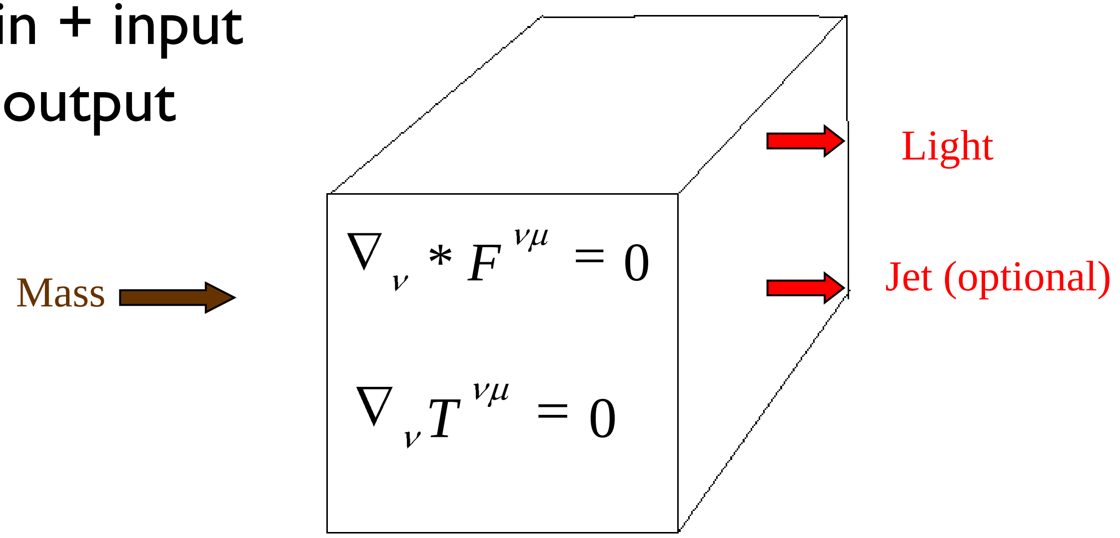
Disk Simulations

The Goal of Accretion Simulations

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



Questions about Black Hole Accretion and Jets

- How do disks accrete?
- How are winds and/or jets produced?
- What disk structures arise naturally?
- What are the properties of disk turbulence?
- What is the disk luminosity and how is that a function of black hole mass and spin (efficiency)?
- Is there a magnetic dynamo in disks? Are there large-scale fields?
- Can we account for different spectral states?
- Origin of *Quasi-Periodic Oscillations* and the Fe Kα line seen in X-ray observations
- What are the properties of the inner disk where it plunges into the hole?
- How does black hole spin affect the jet and the disk?
- How does accretion affect the black hole spin?

The Importance of Magnetic Fields for Accretion Disks and Jets

Magnetic fields make the ionized gas in an accretion disk spiral inward. The *magneto-rotational instability* (MRI) is important in accretion disks because it converts stable orbits into *unstable* motion.

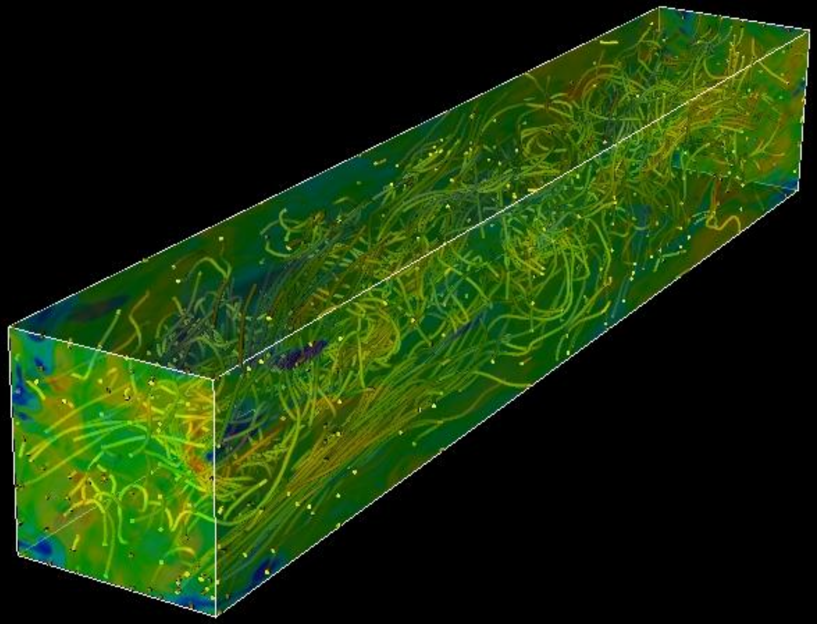
Magnetic fields can create stresses inside the marginally stable orbit around a black hole, significantly increasing total efficiency.

Magnetic fields can extract energy and angular momentum from the disk and from spinning holes to drive jets and outflows.

The identification of a physical mechanism for angular momentum transport makes self-consistent dynamic simulations possible.

Shearing Box Simulations

- Local MHD physics in a differentially rotating environment
- With or without vertical gravity
- Many simulations have been done, with a variety of physics included, box sizes, field strengths, field orientations, etc.



Stratified shearing box with radiation transport

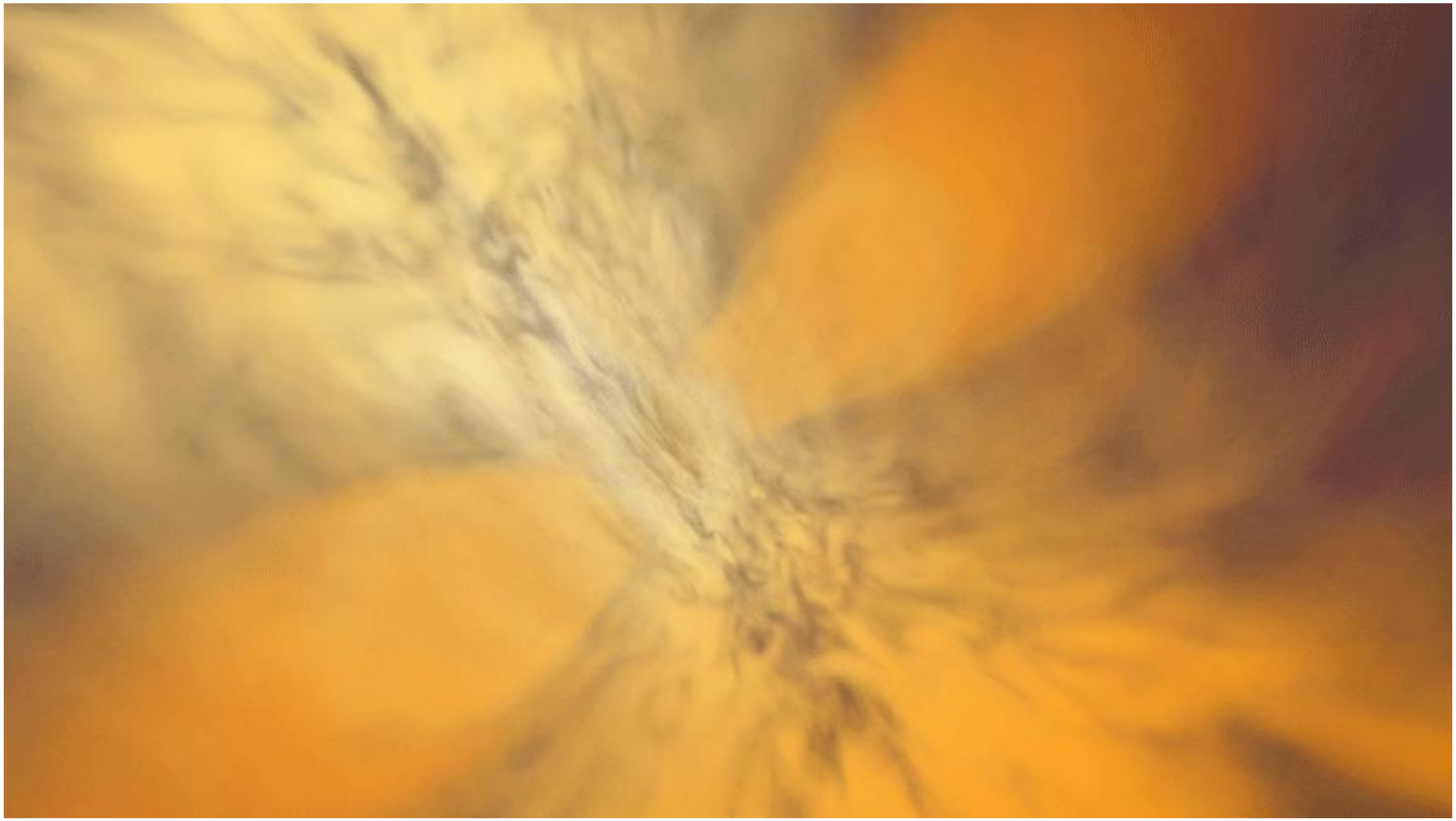
- Flux limited diffusion with Rosseland mean opacity
- Time- and vertically averaged stress proportional to total pressure (not gas or radiation separately). Despite this there is no thermal instability in radiation pressure dominated disks
- Stress determines Pressure, not the other way around:
  $\tau_{r\phi} \longrightarrow P_{\mathrm{total}}$
- Dissipation concentrated near but off midplane. No energetically significant corona. Vertical energy transport dominated by radiation

Hirose, Krolik & Blaes 2009, ApJ, 691, 16

Shearing boxes: MHD Turbulence

- The MRI produces MHD turbulence that transports angular momentum and drives accretion
- Magnetic stress greater than Reynolds stress; total stress proportional to magnetic pressure
- Heating is local: thermalization happens within an eddy turnover time ($\sim \Omega^{-1}$) (Simon et al 2009)
- MRI with net vertical field produces stronger turbulence
- Turbulence levels are influenced by viscosity and resistivity; turbulence increases with increasing magnetic Prandtl number (Fromang et al 2007; Lesur & Longaretti 2007; Simon & Hawley 2009)

Global GR Simulations

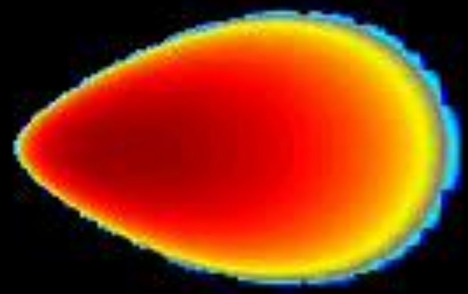


General Relativistic Magnetohydrodynamics Codes

- Wilson (1975)
- Koide et al. (2000)
- Gammie, McKinney & Toth (2003)
- Komissarov (2004)
- De Villiers & Hawley (2003)
- Duez et al. (2005)
- Fragile & Anninos (2005)
- Anton et al. (2005)
- Noble (2008), McKinney (2008)

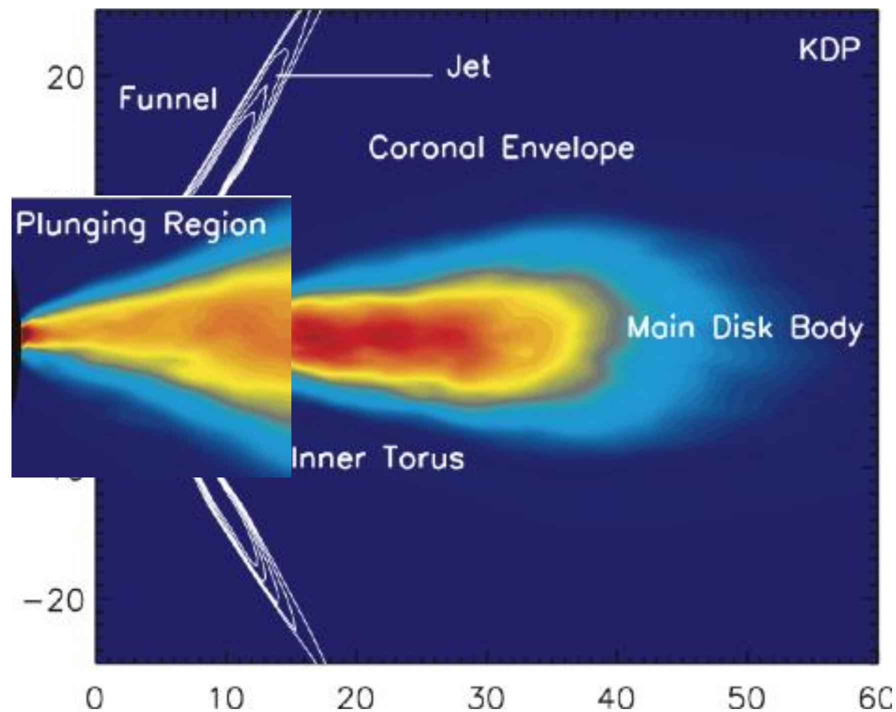
Current Global Simulations

- 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

Stress, Spin and Accretion

- Magnetic stress can operate at and inside the ISCO
- Amount of additional stress depends on field strength and topology near ISCO
- 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

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

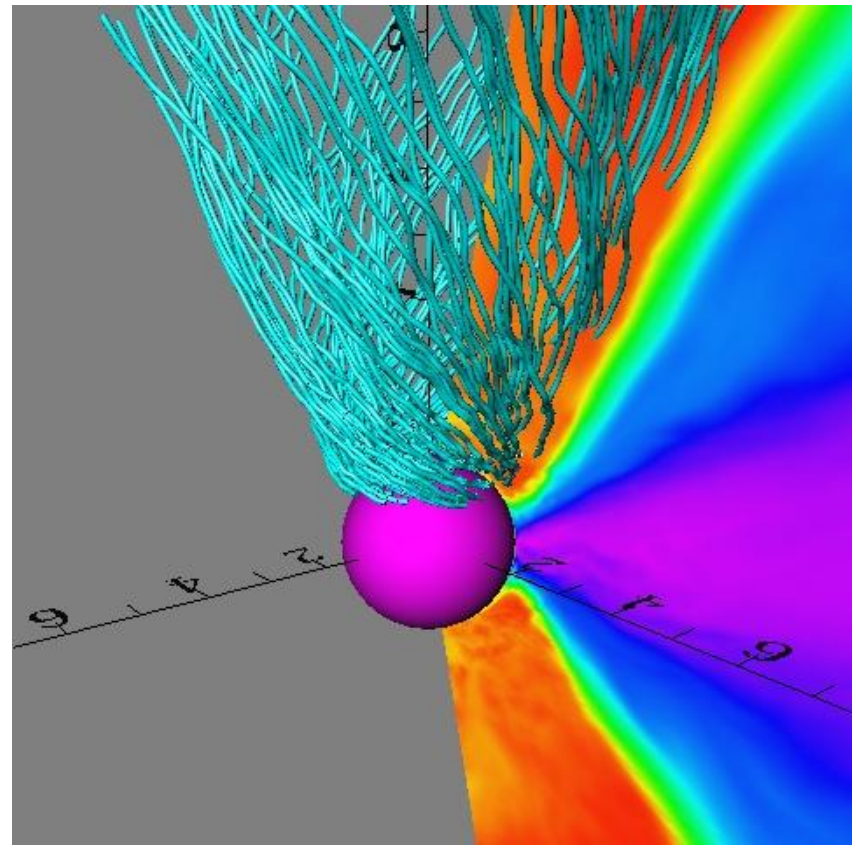
Poynting Flux Jets

Jet Theory

- Disk rotation + vertical field: Blandford-Payne type wind/jet
- Black Hole rotation + vertical field: Blandford-Znajek Poynting flux jet
- Past axisymmetric simulations with initial vertical fields have demonstrated efficacy of these mechanisms.
- Under what circumstances will a large-scale poloidal field be present? Is such a field always required for jet formation? Can such a field be generated in the disk by a dynamo process, or is it brought in from outside?

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

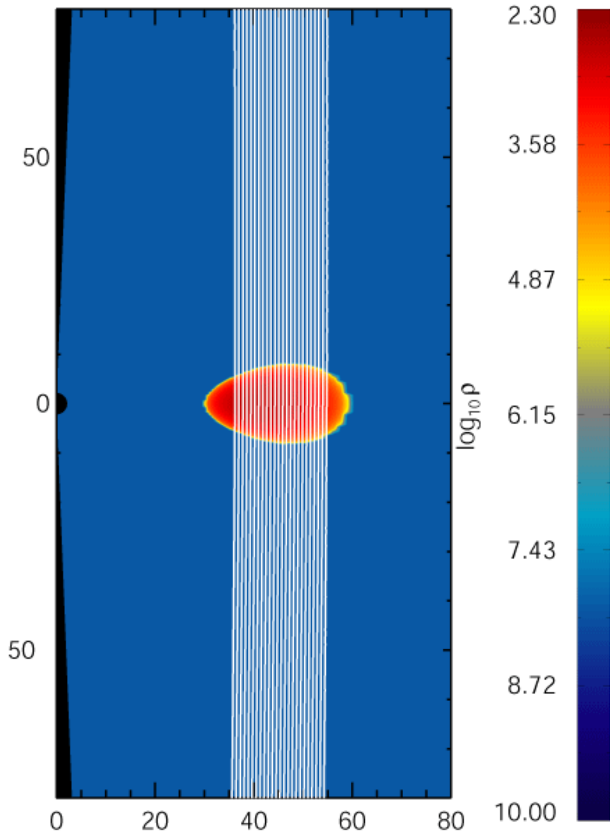
  – Reconnection events between funnel and disk field determine the variability of the jet

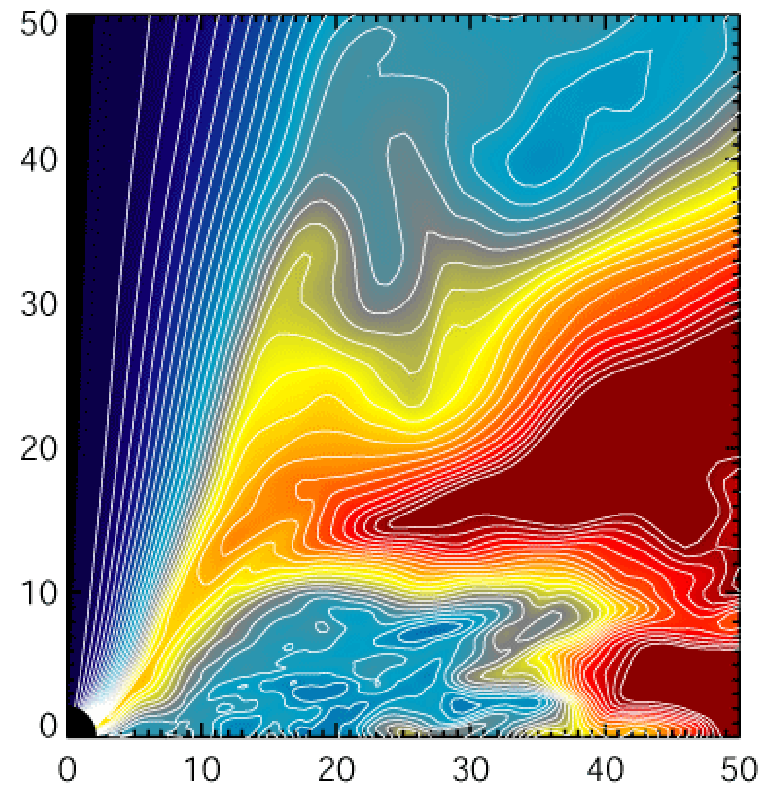
Origin of Large Scale Jet Field

- 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

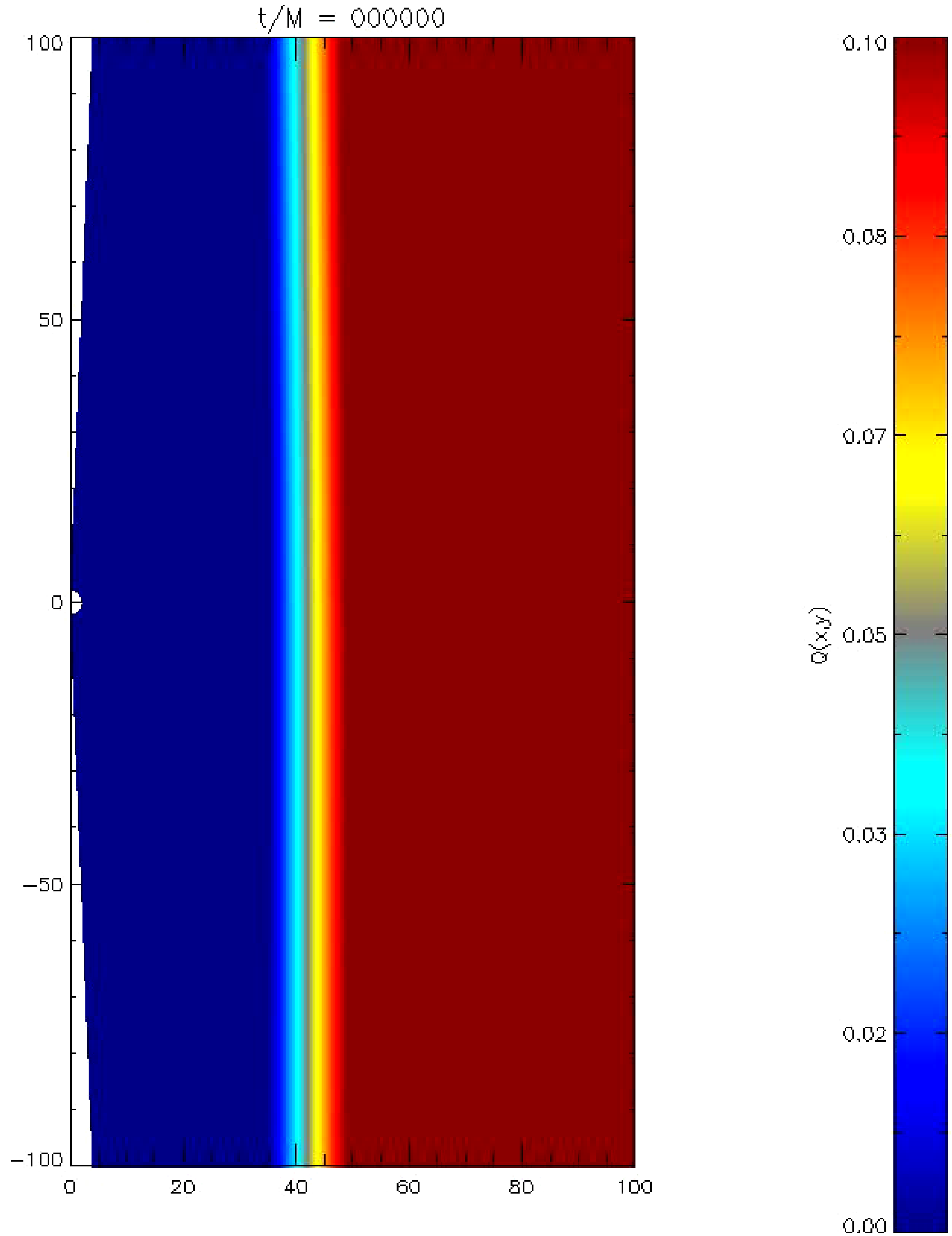




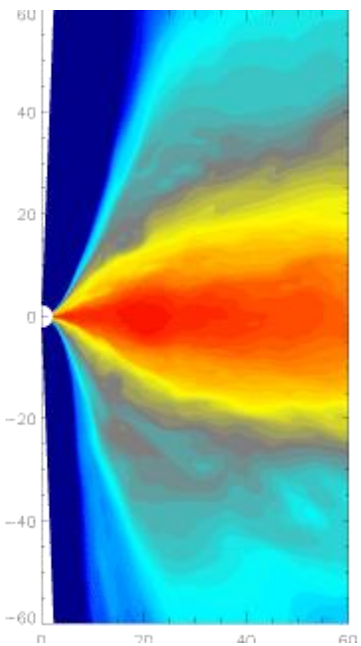
- Can net field be advected inward by MRI turbulent disks? Balance magnetic diffusion/reconnection timescale against accretion timescale?
  - Flux diffusion in the disk can occur but coronal processes seem more efficient at bringing field to the hole

Beckwith et al 2009

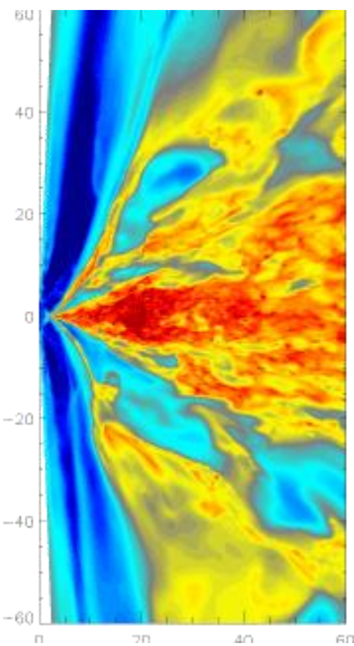
Movie: 3D simulation of vertical field model. Vector potential A_ϕ gradients indicate field line locations



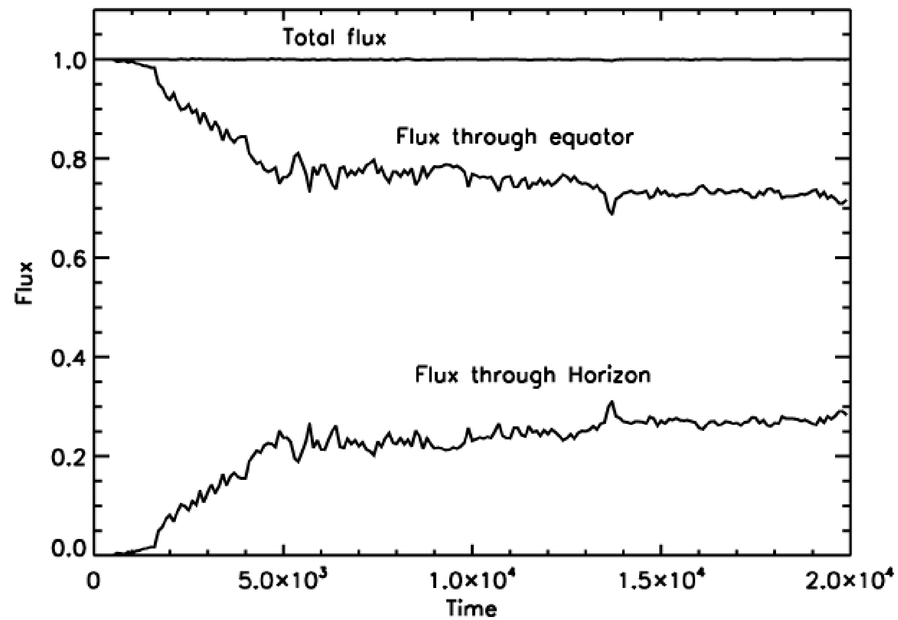
Accumulation of Net Flux



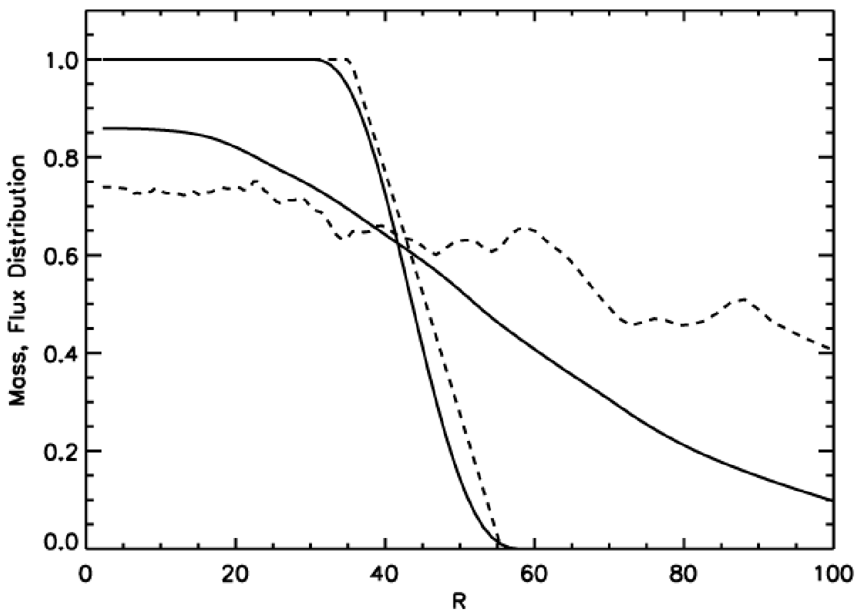
Density

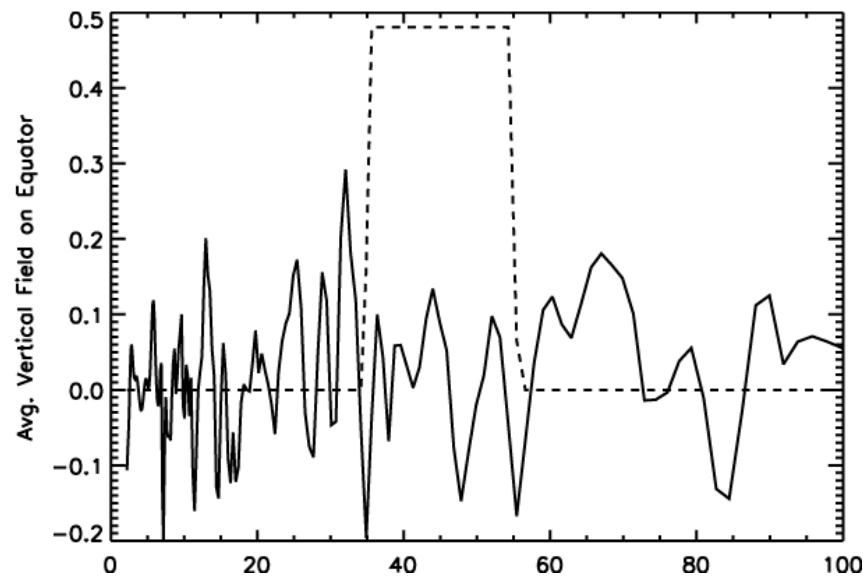


β Parameter



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
- 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

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