General Relativistic MHD Simulations of Black Hole Accretion Disks

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Charles F. Gammie (Illinois)

De Villiers & Hawley 2003, ApJ, 589, 458

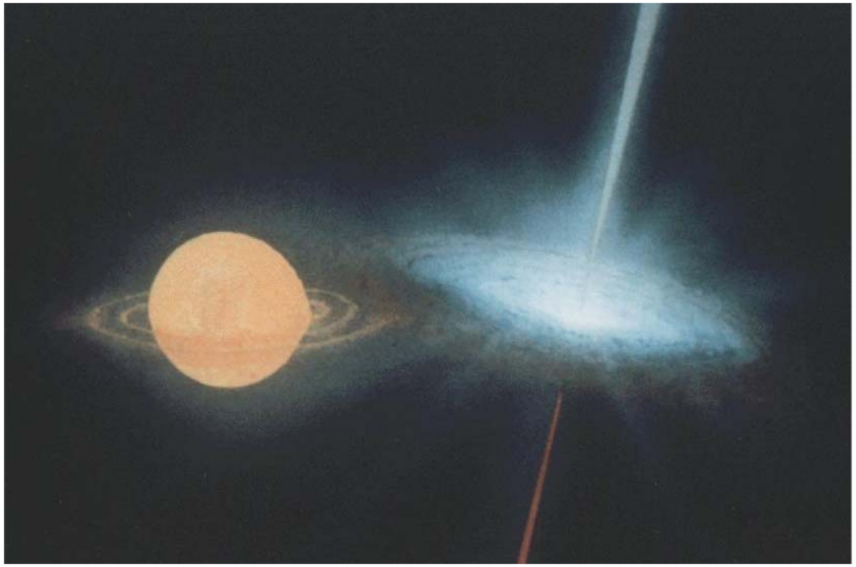
De Villiers, Hawley & Krolik 2003, ApJ, 599, 1238

Hirose, Krolik, De Villiers, & Hawley 2004, ApJ, 606, 1083

De Villiers, Hawley, Krolik, & Hirose 2005, ApJ, in press

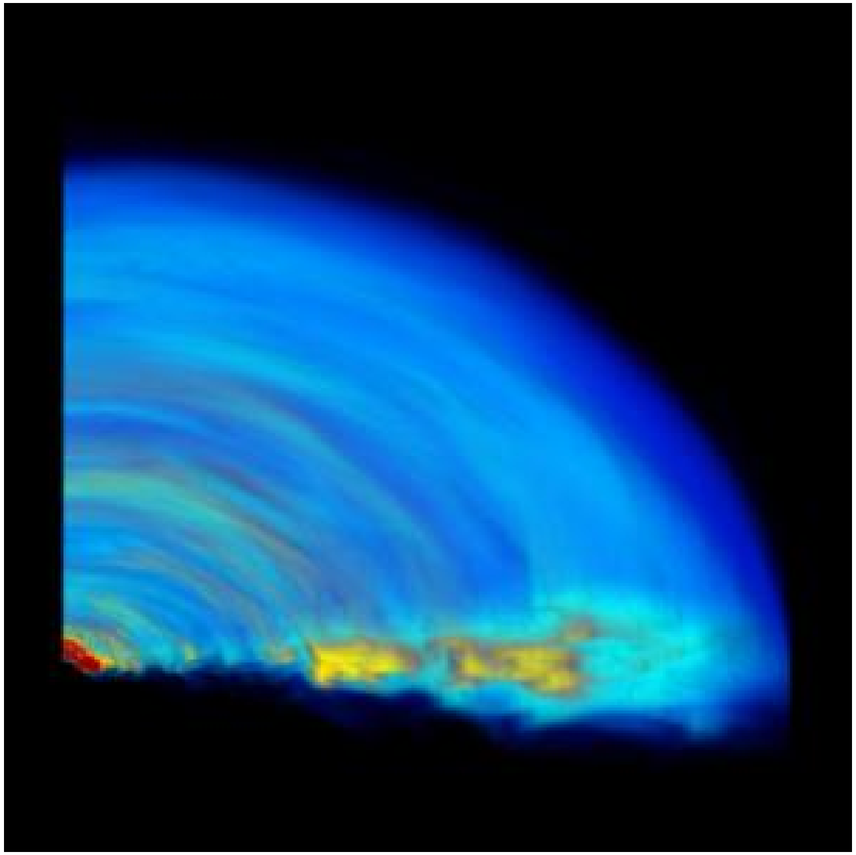
Krolik, Hawley, & Hirose 2005, ApJ, in press

The Accretion Context



Artist’s conception of a black hole binary with accretion disk

Volumetric rendering of density in 3D accretion disk simulation



Simulation Requirements

- Accretion Flows are:
  - Magnetohydrodynamic
  - Three dimensional *(essential but hard!)*
  - Dynamically unstable
  - Turbulent
  - Time-dependent

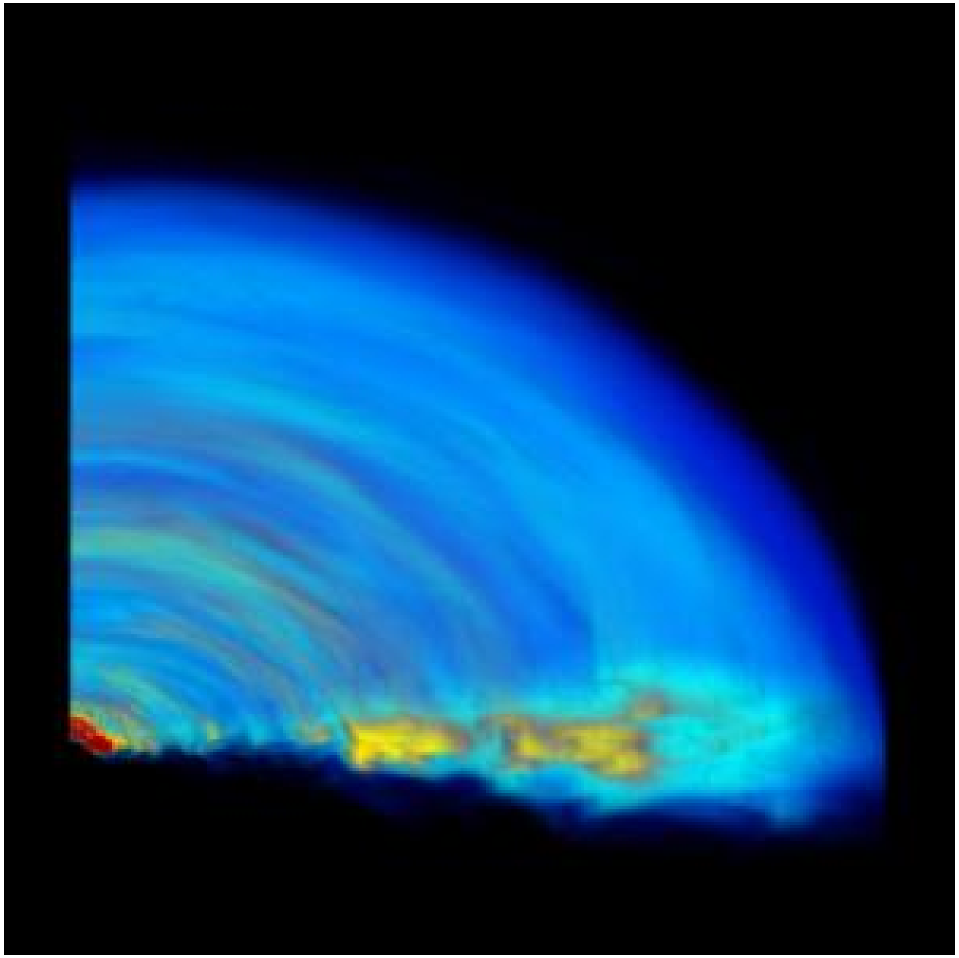
Numerical Simulations Accretion Disks: Local to Global

- Local "Shearing boxes"
- Cylindrical disks (semi-global)
- Axisymmetric global
- Full 3D global simulations – Newtonian, pseudo-Newtonian
- Global simulations in Kerr metric

Summary: Turbulence in Disks – What we have learned from Local Simulations

- Turbulence and angular momentum transport are the inevitable consequence of differential rotation and magnetism because of the MRI
- Hydrodynamic (i.e. non MHD) disk turbulence is not sustained: it has no way to tap *locally* the free energy of differential rotation
- The MRI is an effective dynamo
- The flow is *turbulent* not viscous. Turbulence is a property of the flow; viscosity is a property of the fluid. A high Reynolds number turbulent flow does not resemble a low Reynolds number viscous flow

The Global Picture



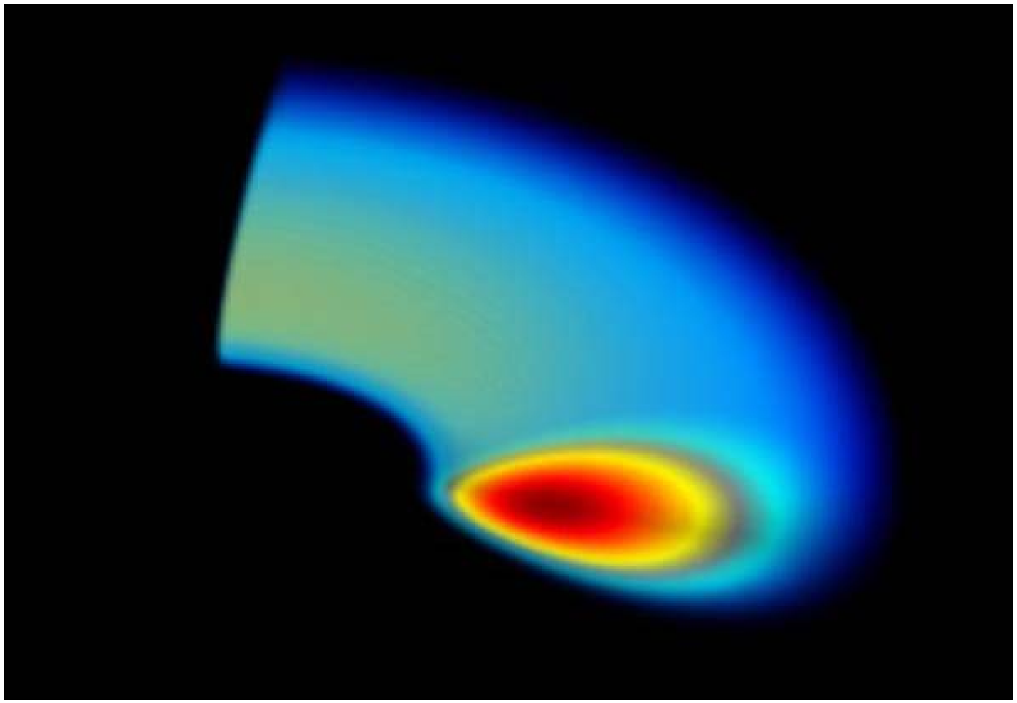
General Relativistic Magnetohydrodynamics Codes

- Wilson (1975)
- Koide et al. (2000)
- Gammie, McKinney & Toth (2003)
- Komissarov (2004)
- De Villiers & Hawley (2003)

GRMHD implementation

- Fixed Kerr Metric in spherical Boyer Lindquist coordinates
- Graded radial mesh - inner boundary just outside horizon; θ zones concentrated at equator
- Induction equation of form
- $F_{\alpha\beta,\chi} + F_{\beta\chi,\alpha} + F_{\chi\alpha,\beta} = 0$
- Baryon Conservation, stress-energy conservation, entropy conservation (internal energy); no cooling
- First order, time-explicit, operator split finite differencing
- Similar to ZEUS code

Simulations around a Kerr hole from an Initial Magnetized Gas Torus



Initial poloidal field loops

$\beta = 100$

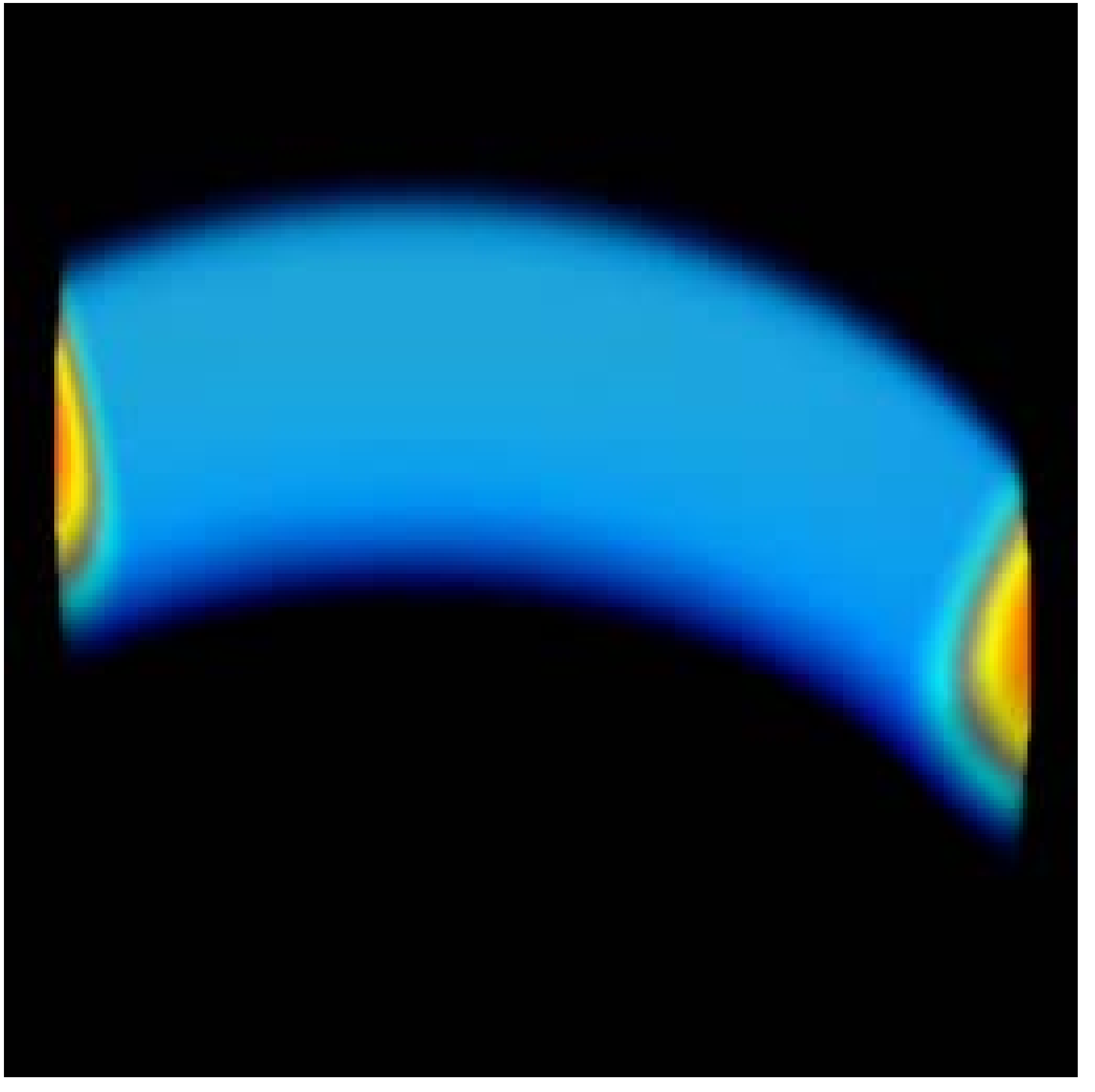
Outer boundary 120M

Colors indicate density

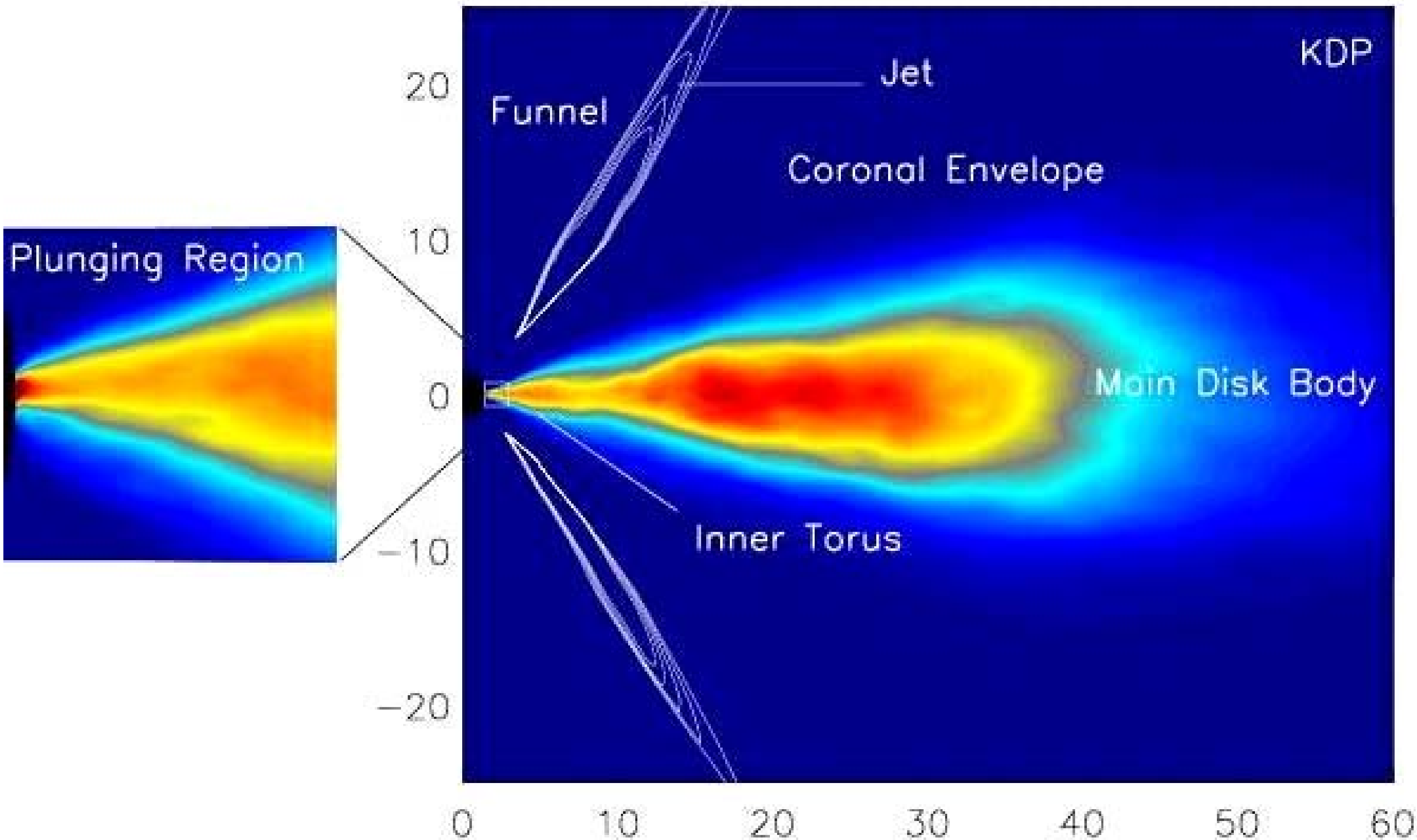
r = 25 M

Ensemble of black hole spins:
a/M = 0, 0.5, 0.9, 0.998

Global Disk Simulation



Accretion flow structures

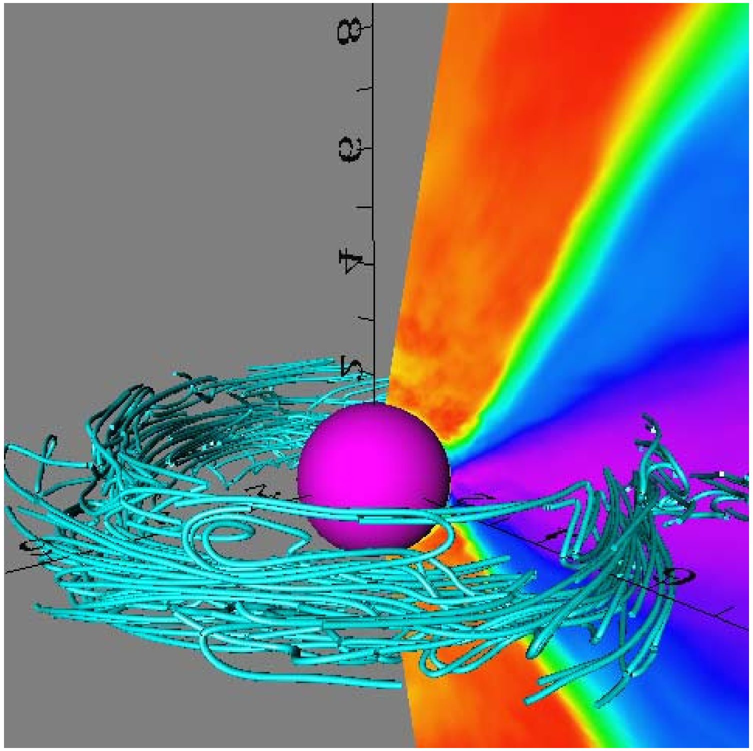


Properties of the Accretion Disk

- Accretion disk angular momentum distribution near Keplerian
- Disk is MHD turbulent due to the MRI
- No abrupt changes at marginally stable orbit; density, velocity smooth & continuous
- Large scale fluctuations and low-m spiral features
- Low-spin models have come into approximate steady state
- Relative accretion rate drops as a function of increasing black hole spin

Field in main disk

- Field is tangled; toroidal component dominates
- Field is sub-equipartion; $\beta > 1$
- Field is correlated to provide stress. Average stress values 0.1 to 0.01 thermal pressure; stress ~ ½ magnetic pressure
- Stress continues inside marginally stable orbit

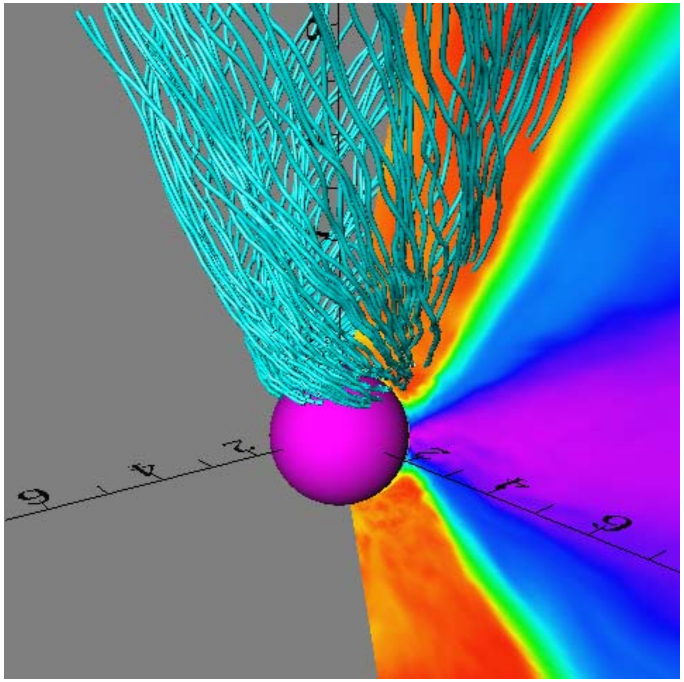


What about Jets? A combination of Rotation, Accretion, Magnetic Field

- Young stellar objects
- X-ray binaries – accreting NS or BH
- Symbiotic stars – accreting WD
- Supersoft X-ray sources – accreting WD
- Pulsars – rotating NS
- AGN – accreting supermassive BH
- Gamma ray burst systems

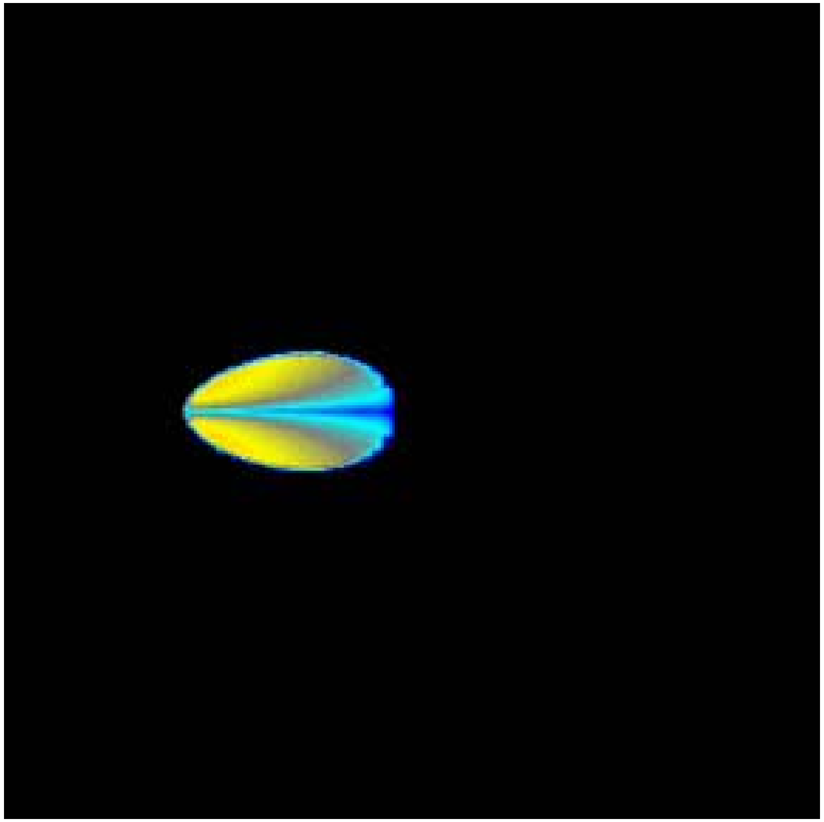
Funnel Properties

- Funnel is evacuated
- Poloidal radial field created by ejection of field from plunging inflow into funnel
- Field in pressure equilibrium with corona
- Toroidal field can be generated by black hole spin – outgoing Poynting flux
- Unbound mass outflow at funnel wall



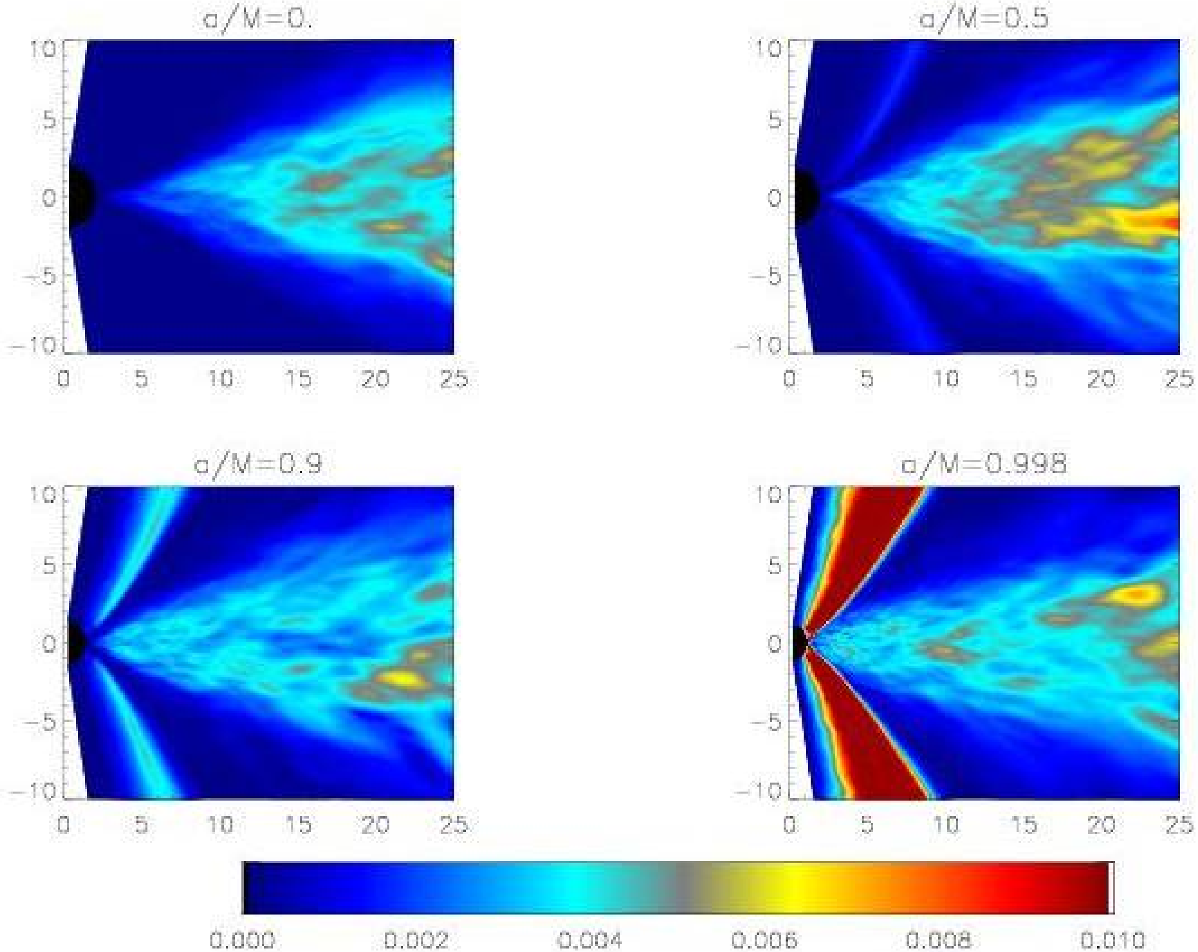
Origin of funnel field

- Magnetic field is ejected into the centrifugally-evacuated funnel
- Spin of the black hole creates outgoing EM energy



Radial magnetic field energy density

Poynting Flux for Different Black Hole Spins



Jet Luminosity

a/M	η_{jet}	η_{jet} / η_{ms}	Poynting
0.0	0.002	0.03	0.06
0.5	0.013	0.16	0.34
0.9	0.029	0.18	0.47
0.998	0.18	0.56	0.87

Funnel and jets: a summary

- Outflow throughout funnel, but only at funnel wall is there significant mass flux
- Outgoing velocity ~0.4 - 0.6 c in mass flux
- Poynting flux dominates in funnel
- Jet luminosity increases with hole spin
- Fraction of jet luminosity in Poynting flux increases with spin
- Both pressure and Lorentz forces important for acceleration

Conclusions

What disk structures arise naturally?

Near-Keplerian disks, surrounded by magnetized corona

What are the properties of disk turbulence?

Turbulence is driven by the MRI. Highly correlated fluctuations transport angular momentum, large scale fluctuations and low-m spiral features. Toroidal fields dominate. Stress ~ ½ magnetic pressure

Is there a dynamo?

Yes, magnetic field is amplified and sustained at sub-thermal equipartition levels; funnel filled with large-scale radial field initially created in the plunging accretion

Conclusions (cont)

Are winds and/or jets produced?

Winds are a natural outcome (without cooling); funnel wall jet; evacuated funnel with magnetic field forms

What are the properties of the inner disk edge?

Location of inner edge time varying; physical quantities vary smoothly; stress not zero at or inside marginally stable orbit. Interaction between spinning black hole and disk.

How does black hole spin affect accretion?

Increasing efficiency with increasing spin. Black hole spin adds to jet power. High spin holes are being spun down. Black hole transfers angular momentum to accretion flow.