Launching Relativistic Jets

John F Hawley

University of Virginia

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Jets in the 80's

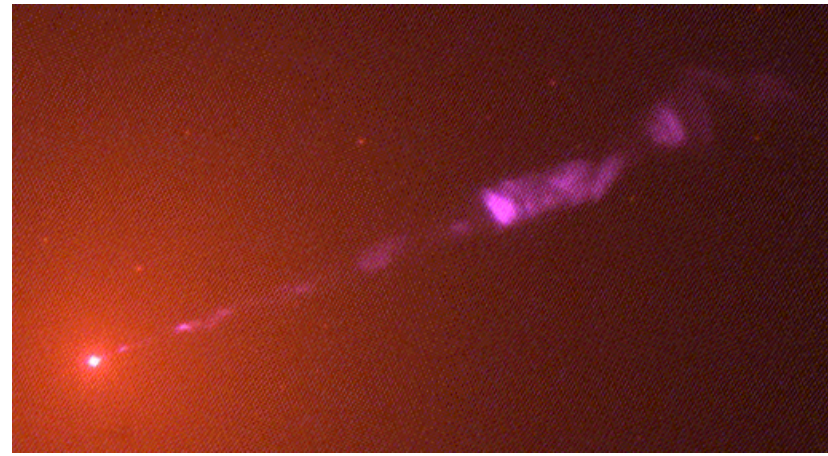
An imperfect recollection

- VLA slowly realizing its capability
- Ubiquity of jet phenomenon beginning to be recognized
- Are jets evidence for supermassive black holes in AGN?
- Radio galaxies at high redshift – implications for cosmology
- "Sidedness" of jets?
- Jet morphology and interaction with environment
- Hydrodynamic 2D cylindrical jet simulations
- Collimation mechanisms?
- Thick tori – existence and stability?
- Jet acceleration: hydrodynamic, radiation driven, magnetic fields?

De Young, D. S., *Jets in Extragalactic Radios Sources*, Nature, 1984
De Young, D. S., *Astrophysical Jets,* Nature, 1991

Astrophysical Jets Everywhere

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



The Ubiquity of Jets suggests that they result from general conditions.
Gravity + Rotation (disk and/or central star) + Magnetic fields
Source of Energy: Accretion or rotation of central star

The Importance of Magnetic Fields

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 spinning holes and drive jets.

Jet Theory

- Disk rotation + vertical field: Blandford-Payne type wind/jet
- Black Hole rotation + vertical field: Blandford-Znajek Poynting flux jet
- Idealized models and 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?

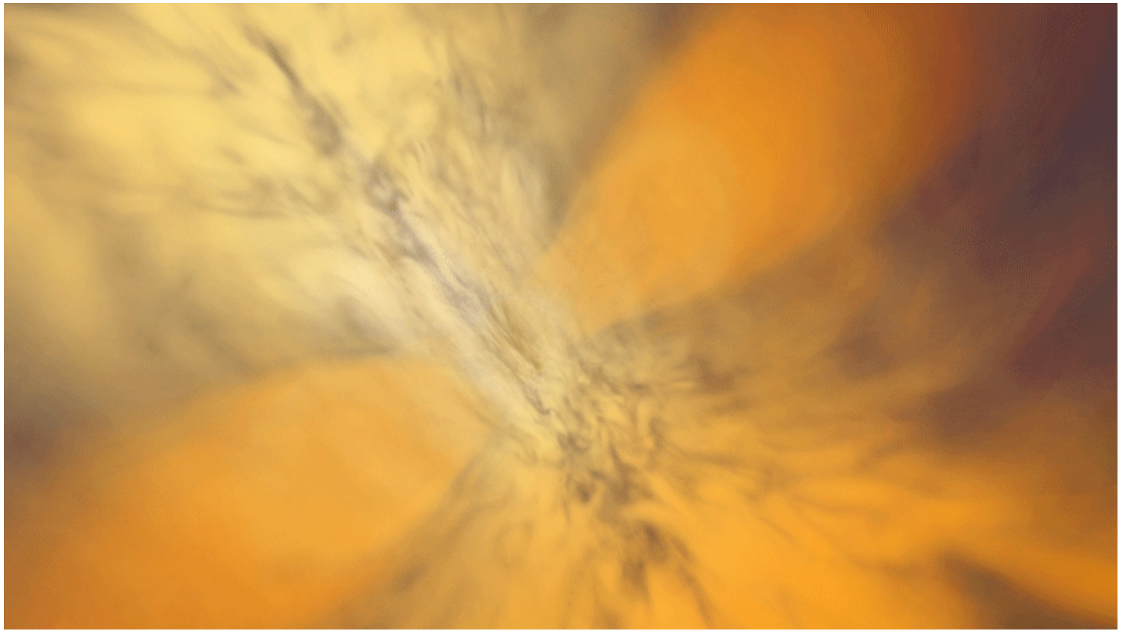
Simulating Global Accretion Disks

The role of magnetic fields:

Jets and Stress

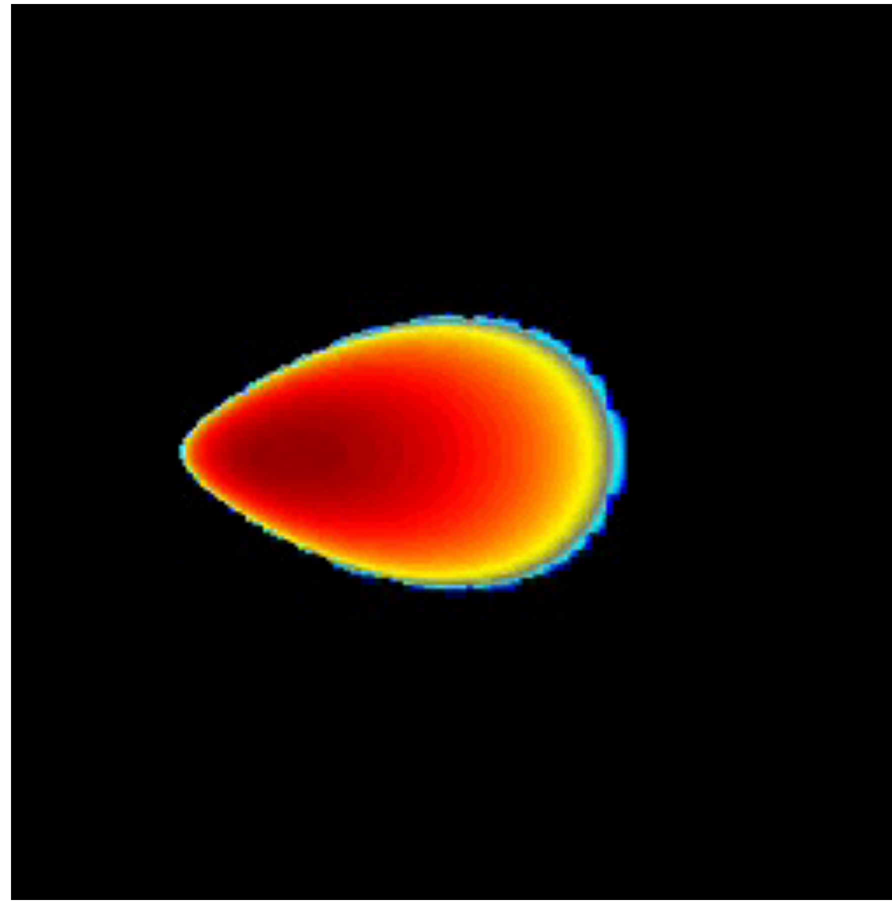
Global Simulations

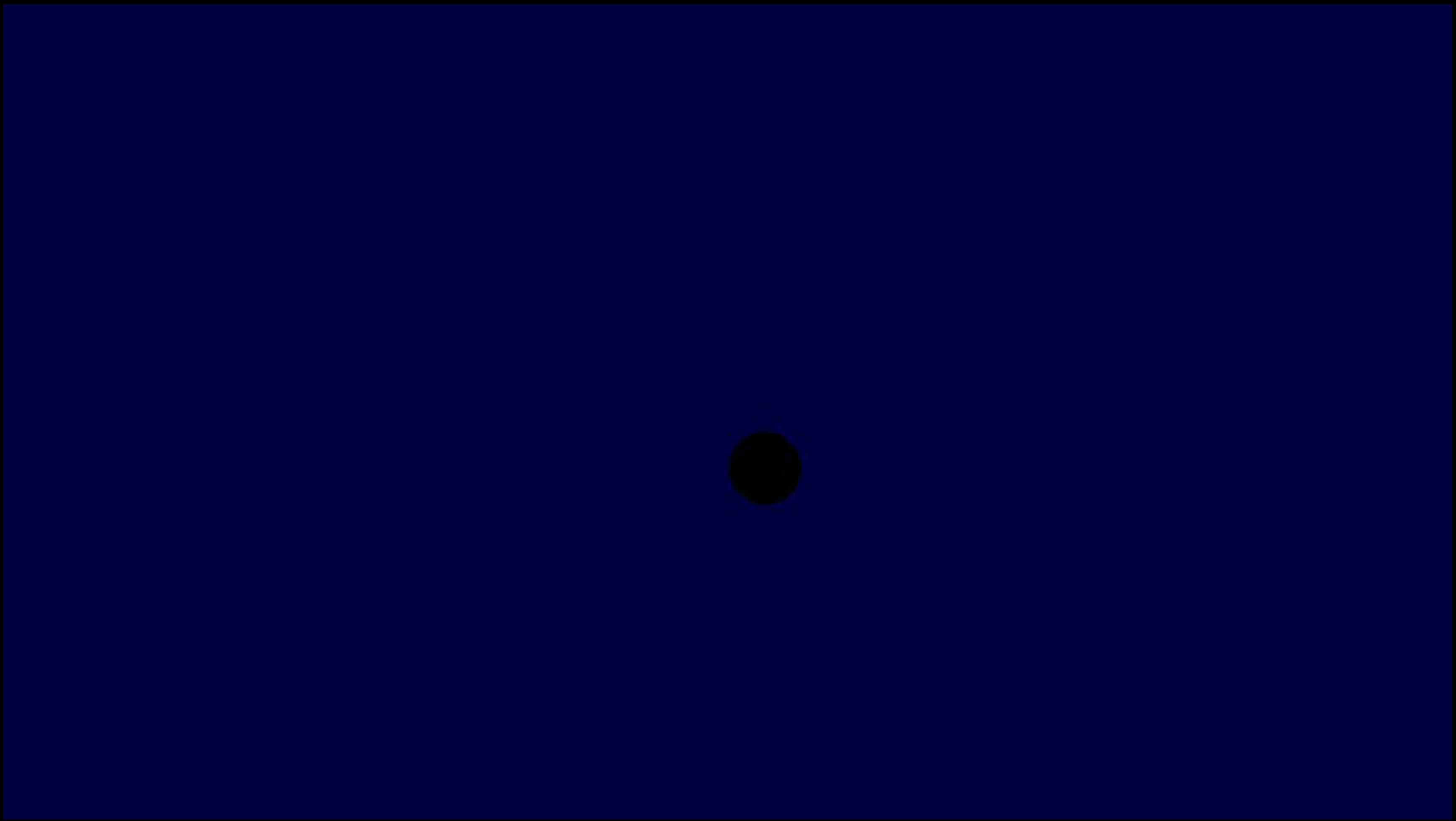
- Global problem difficult to resolve spatially: turbulent scales to parsecs
- Wide range of timescales
- Presently limited to simple equation of state
- Dissipation, heating, thermodynamics too limited
- Only simple radiative losses; no global radiative transfer
- System scales with M; density set by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



General Observations: Global Simulations with Initial Dipole Field

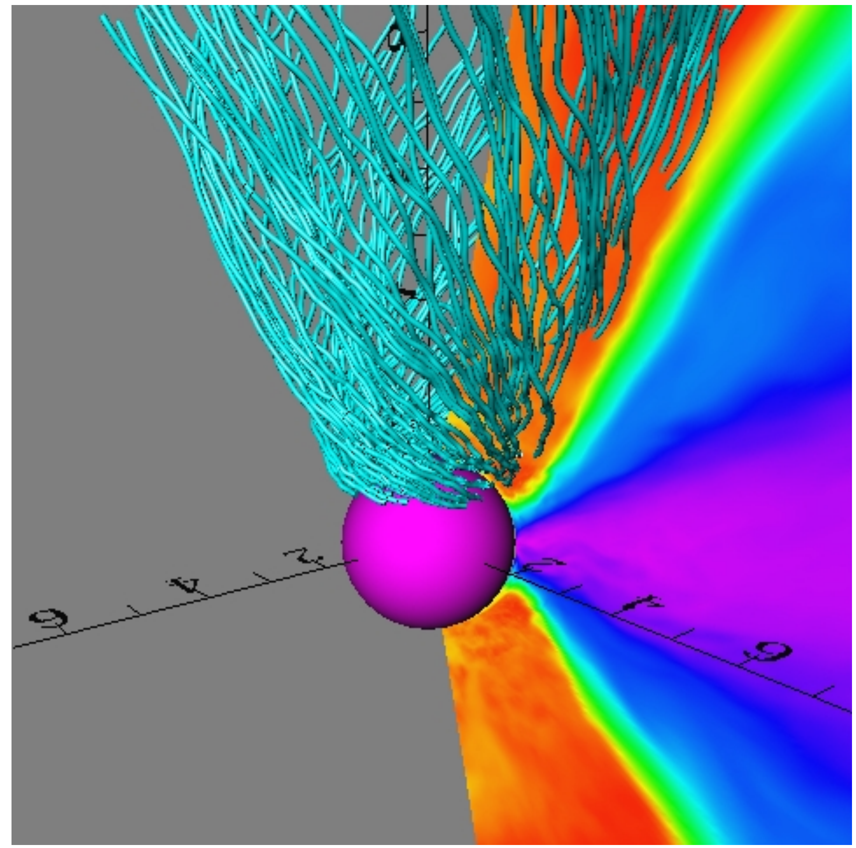
- Accretion disk angular momentum distribution near Keplerian
- Disk is MHD turbulent; internal stress due to the magnetorotational instability
- No abrupt changes at marginally stable orbit
- Large scale fluctuations and low-m spiral features
- No stress edge; enhanced efficiency
- Transfer of angular momentum from black hole to disk
- Implications for the equilibrium spin of the black hole
- Some studies of disk tilt/mis-alignment (e.g., Fragile et al.)





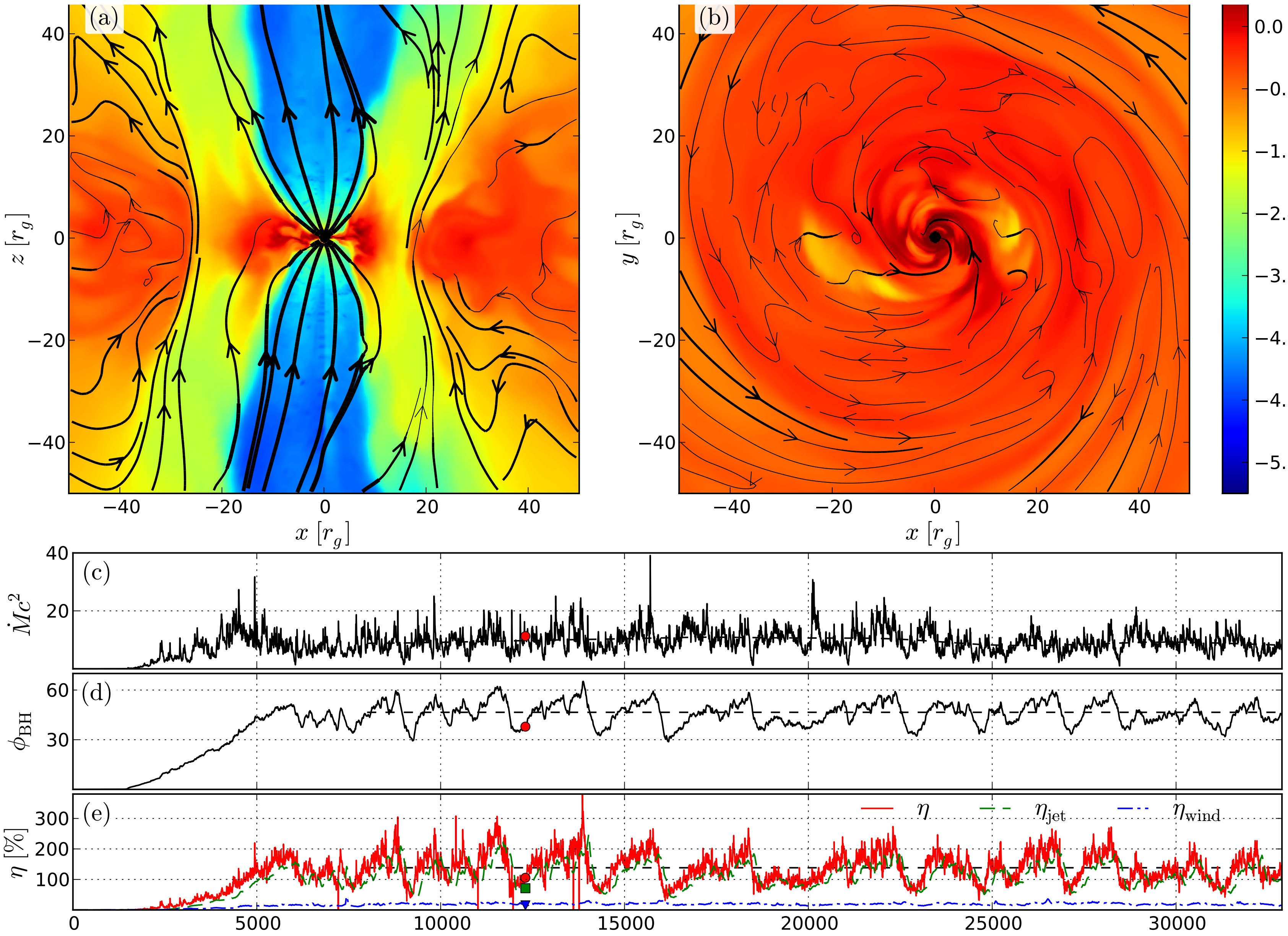
Simulation Results: Jets

- Poynting flux dominated within funnel; only at funnel wall is there significant mass flux
- Jet luminosity increases with hole spin – Poynting flux jet is powered by the black hole
- Fraction of jet luminosity in Poynting flux increases with spin
- Both pressure and Lorentz forces important for acceleration
- Existence of funnel jet depends on establishing radial funnel field
- Jet power depends on field strength, total flux
- Lorentz factor Γ for jet depends on mass loading – this is not reliable in current simulations



Substantial Jet Energy Efficiency for Rapid Spin: Dipole Initial Field

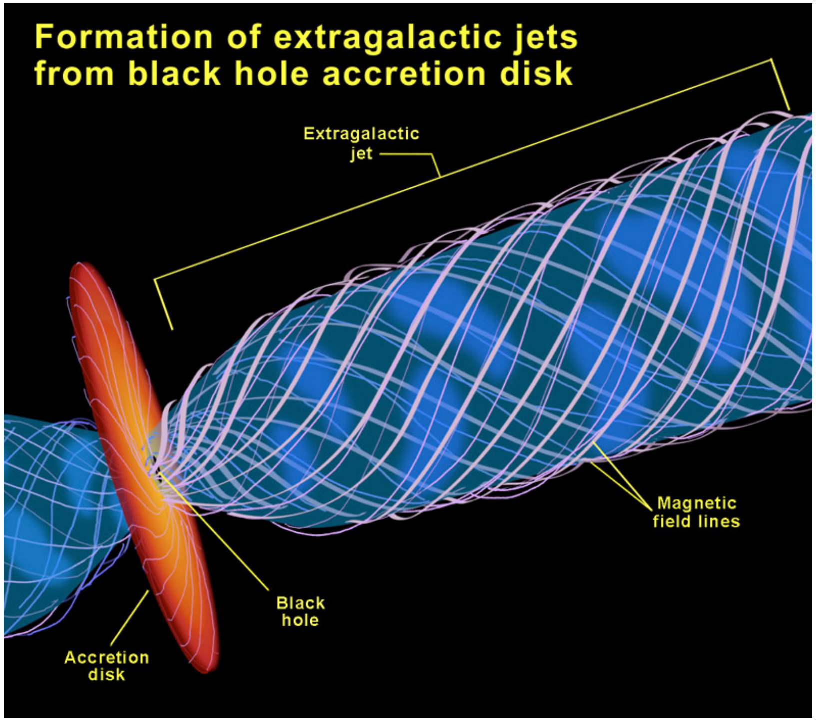
a/M		η_{EM}	η_{NT}
-0.9		0.023	0.039
0.0		0.0003	0.057
0.5		0.0063	0.081
0.9		0.046	0.16
0.93		0.038	0.17
0.95		0.072	0.10
0.99		0.21	0.26



Tchekhovskoy, McKinney & Narayan 2012

Origin of Large Scale Jet Field

- Is net vertical flux required, or just large-scale poloidal field?
- Can significant large-scale poloidal field be generated solely by the MRI within turbulent disks?
- Can net field be advected inward by MRI turbulent disks? Balance magnetic diffusion/reconnection timescale against accretion timescale
- How does the presence or absence of a jet relate to the overall state of the disk and its magnetic field?



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

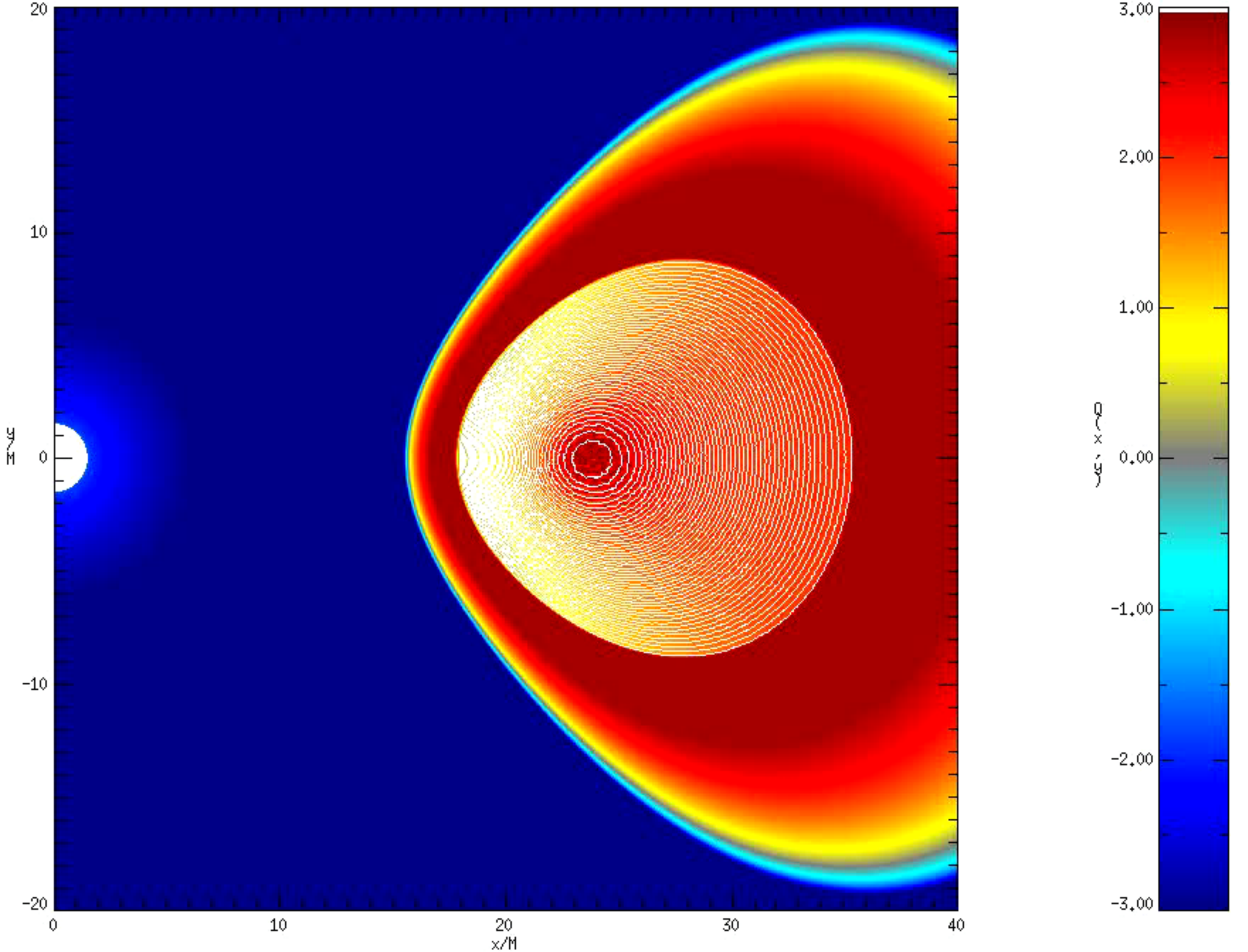
- This is not true for the jet:

  – 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

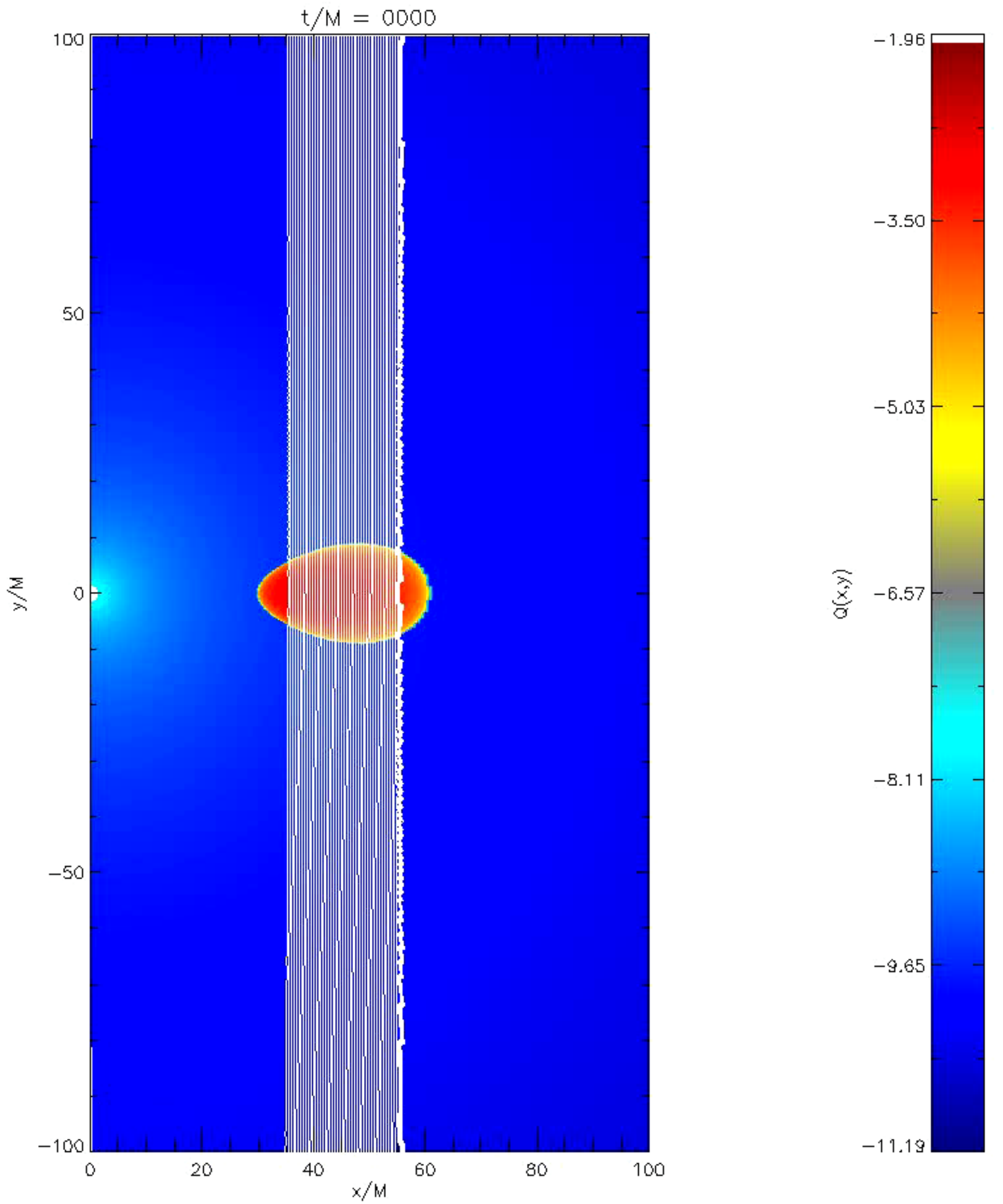
Origin of the poloidal Funnel Field
From an initial dipole
2D Simulation – thick torus
Color: Plasma Beta
White field lines



20
10
0
-10
-20
y/M
0
10
20
30
40
x/M
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
Q(x,y)

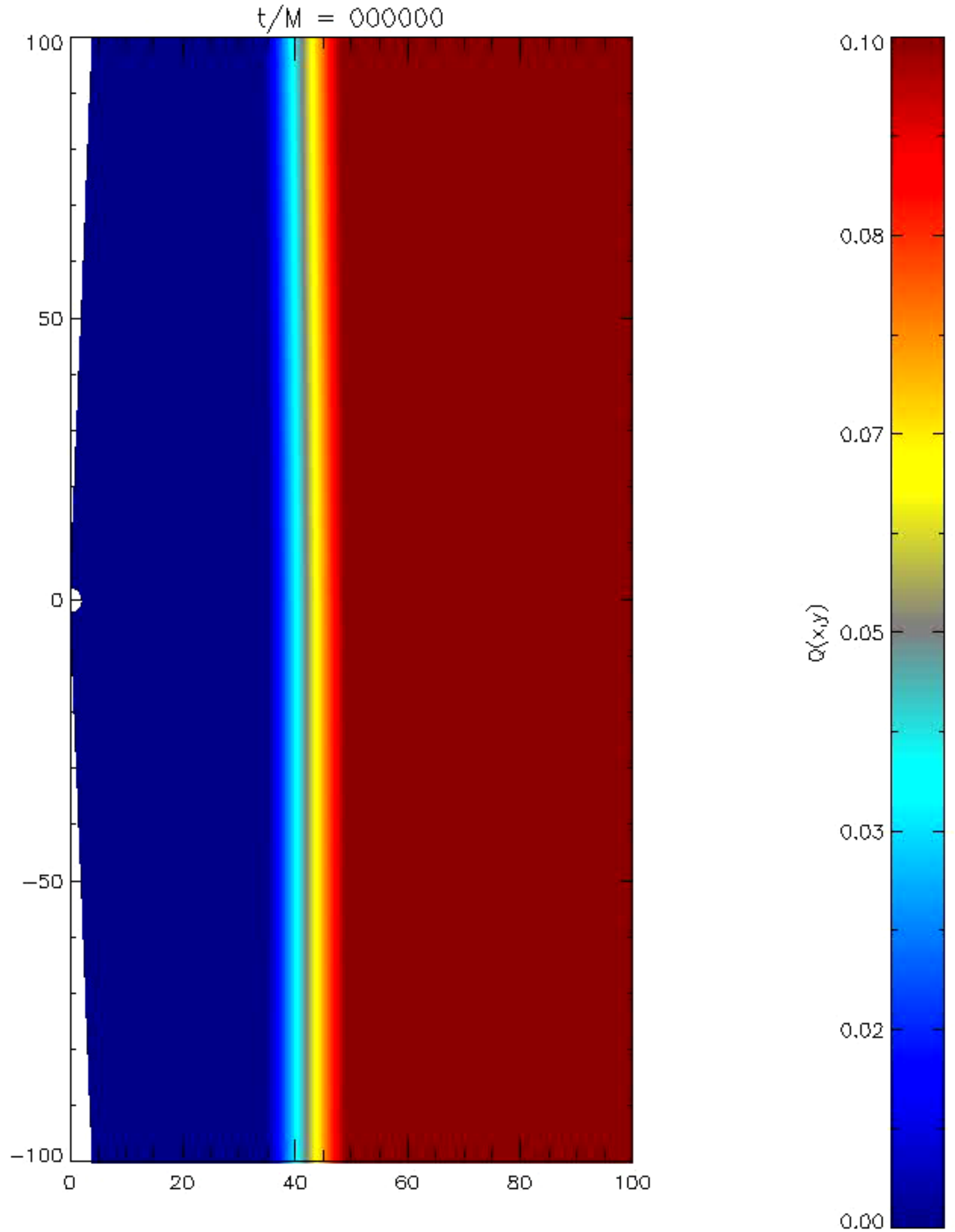
Radial Advection of Net Vertical Field

Can net field be brought in from large distances?



t/M = 0000
100
50
0
−50
−100
y/M
0
20
40
60
80
100
x/M
−1.96
−3.50
−5.03
−6.57
−8.11
−9.65
−11.19
Q(x,y)

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



Transport of Net Flux

- *Global* processes can dominate over local processes
- Within the turbulent disk (and in turbulent shearing box simulations) magnetic flux can “diffuse”
- MRI turbulence (“alpha viscosity”) in disk effective at transporting angular momentum and mass; rapid reconnection prevents effective transport of net flux
- Reconnection can make net flux transport nonlocal
- “Turbulent magnetic Prandtl number” description not particularly useful

Origin of Large Scale Jet Field: Key Questions

- 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 (consequence of initial conditions)
- 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; there is evidence for a dynamo process in disks, but the effect is mainly to sustain MRI
- 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 are related to total pressure in near-hole disk; rough equipartition
  - Initial collimation provided by disk and corona pressure

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 except that generally field energy is subthermal; field topology, net field, resistivity and Prandtl number….
  - “α Begone!” (Blaes 2007)
- Poynting flux jet power comes from black hole spin
  - Under what circumstances does required axial field become established?
  - Can net field be transported inward? Disk transport seems inefficient but coronal mechanisms may be present
  - Large scale fields also seem to be required for jets that originate in disks