GR/MHD SIMULATIONS OF JET-LAUNCHING

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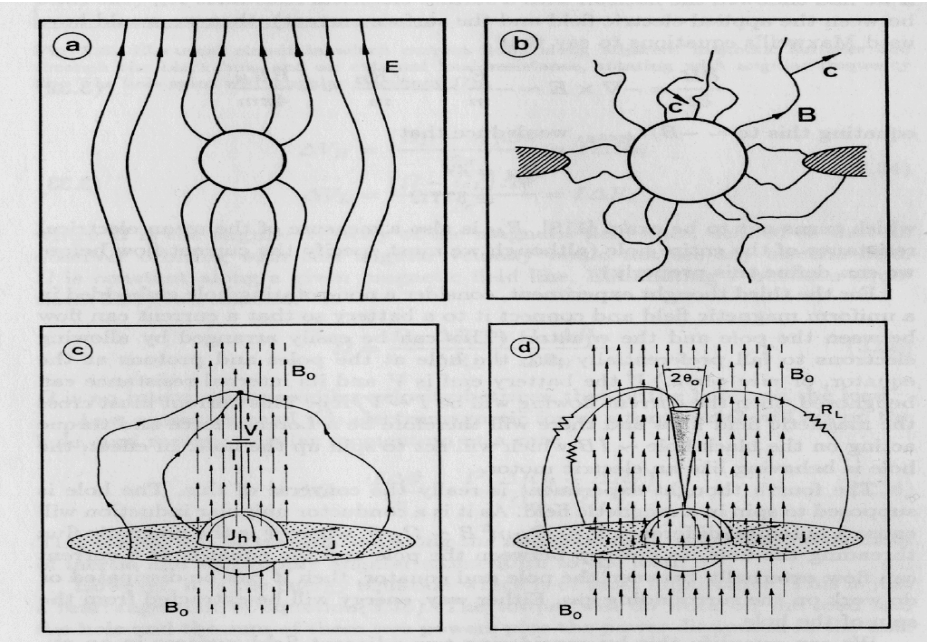
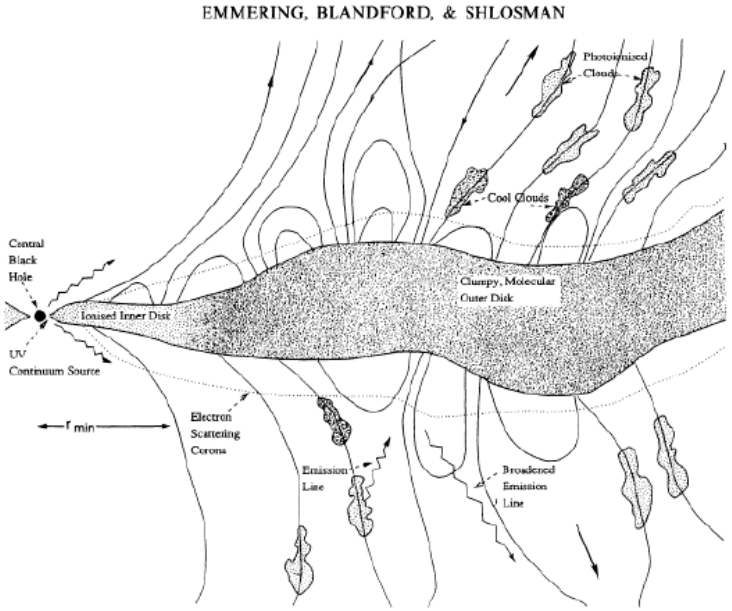
Magnetic Fields + Rotation?

From Thorne, Price & MacDonald





rotating black holes ala Blandford-Znajek?

disk winds ala Blandford-Payne?

Many Questions

- What determines the magnetic field strength and structure?
- Is net magnetic flux necessary?
- Is black hole rotation or disk orbital rotation more important?
- What is the relative importance of magnetocentrifugal forces, pressure gradients, radiation forces?
- What determines the mass-loss rate?

Simplest Approach:
Are Jets Byproducts of Accretion?
Answer by Simulation

Code Physics:

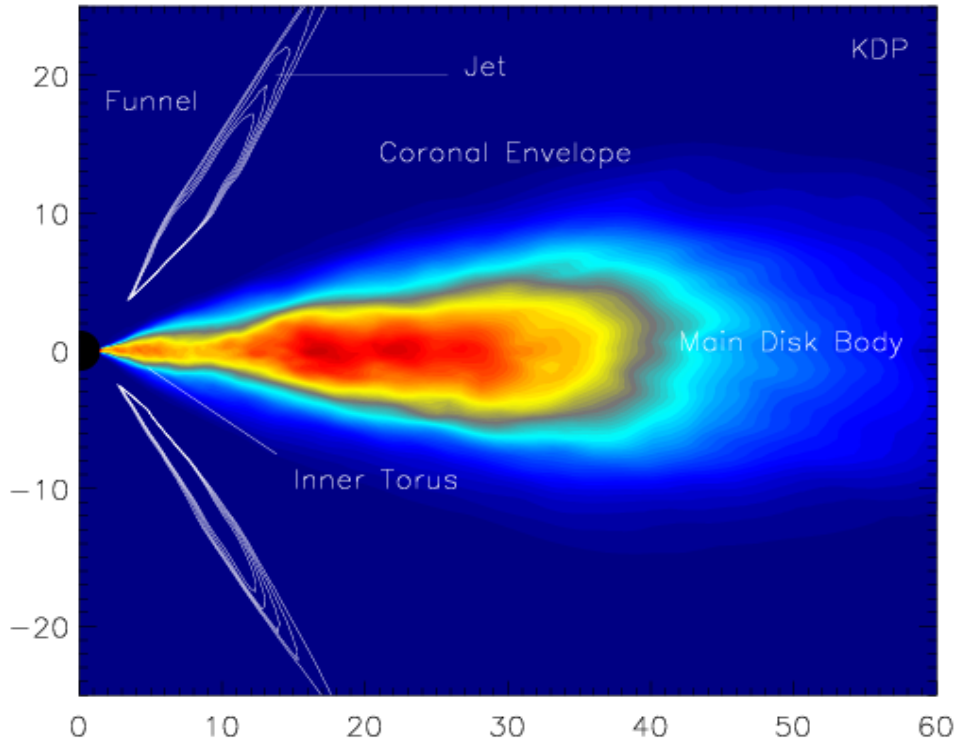
See also McKinney & Gammie, Komissarov, Nishikawa et al. poster

- Full GR (Kerr metric)
- 3-d MHD
- adiabatic internal energy

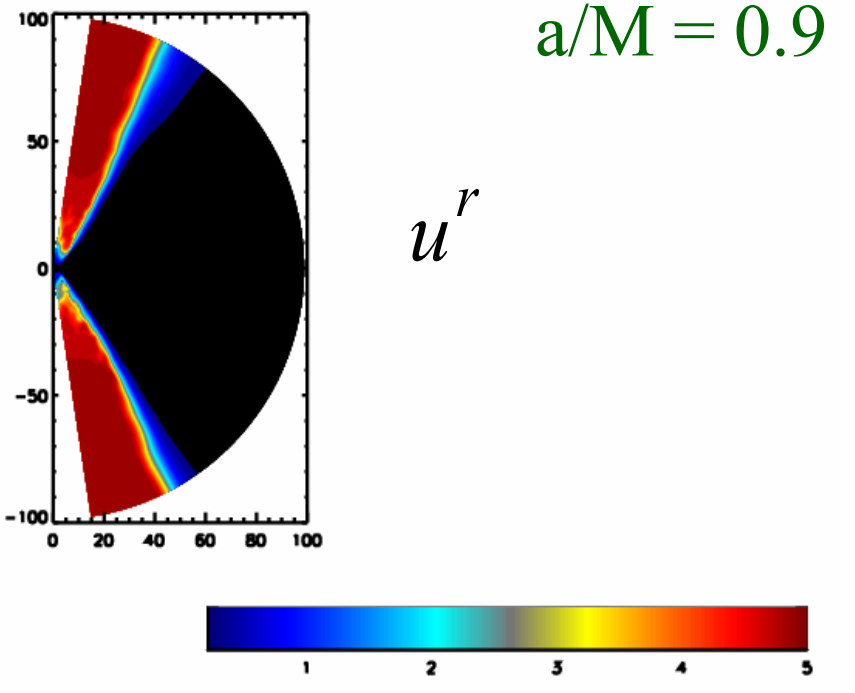
Simulation Specifics:

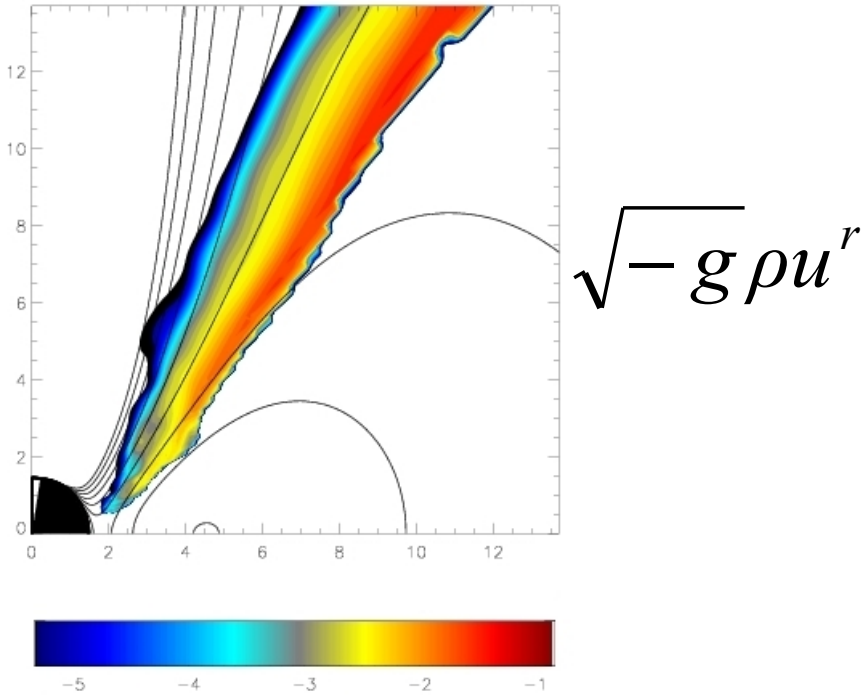
- Hydrostatic torus in initial state
- Initial field purely poloidal, no net flux
- Duration 10000 M

Global Structure



The Jet: a Two-Component Outflow

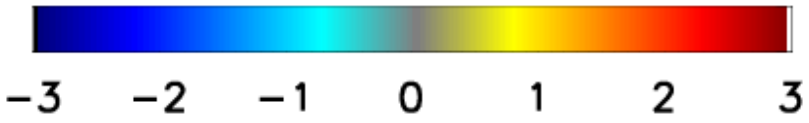


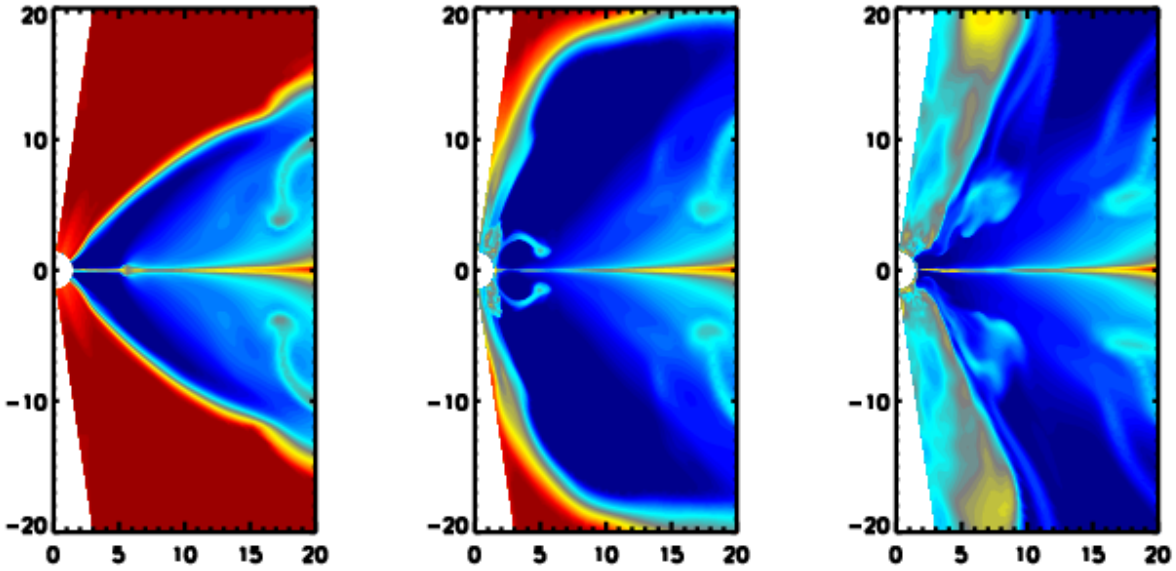


a relativistic magnetically-dominated filled cone

a slower matter-dominated hollow cone

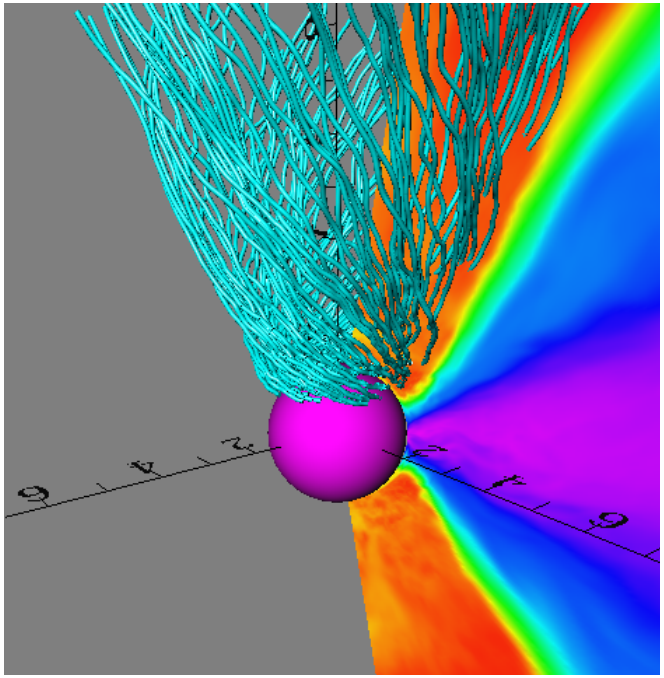
Large-Scale Poloidal Field is Generated Spontaneously

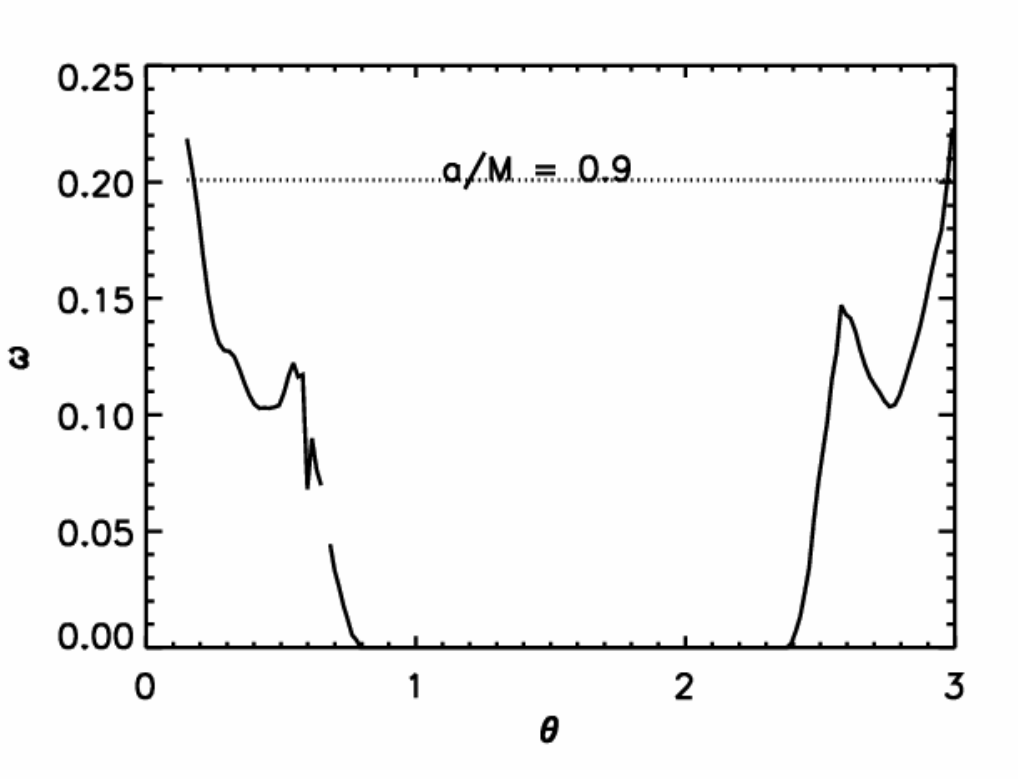




Plasma beta at intervals of 80M

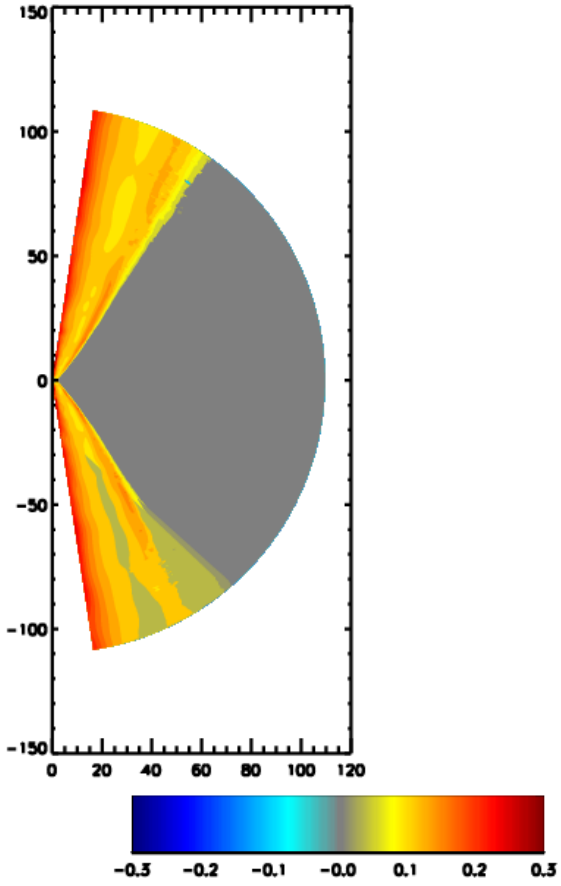
Rotating Space-Time Turns the Magnetic Crank

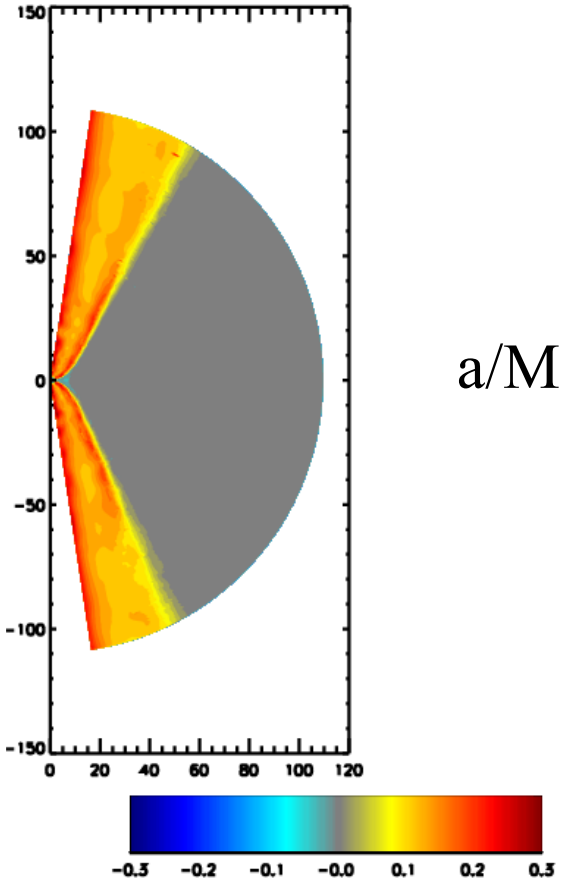




Fieldline Rotation Follows the Hole, not the Accreting Matter

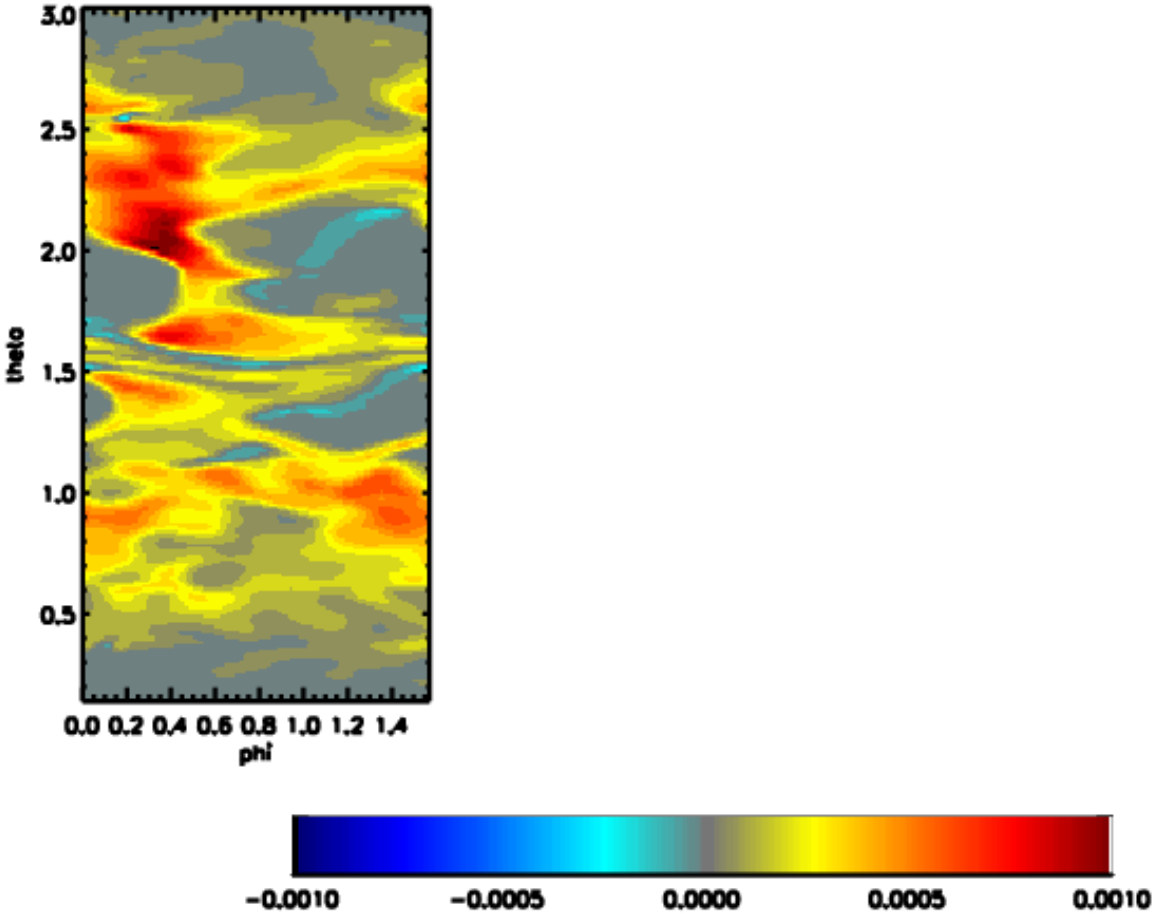
a/M = 0.9



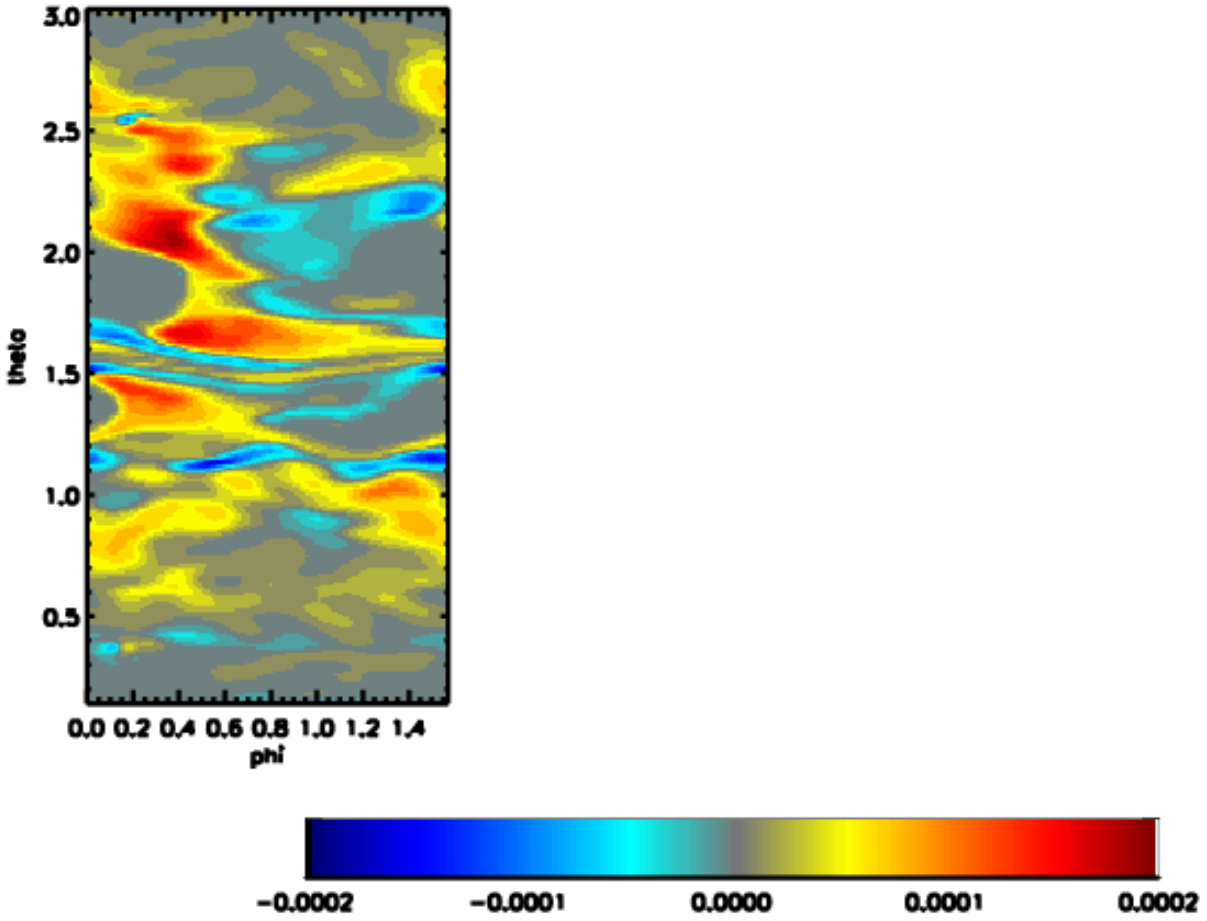


a/M = -0.9

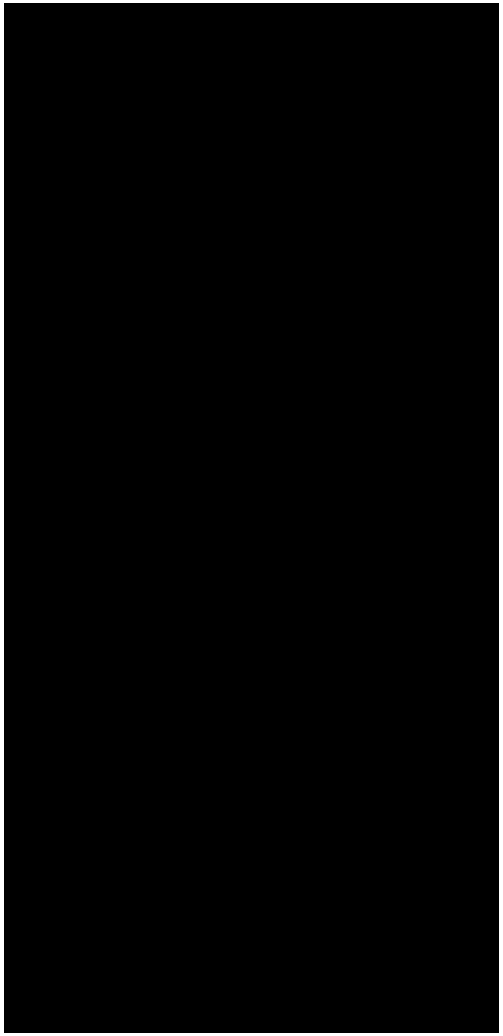
EM Torque from Spinning Black Holes



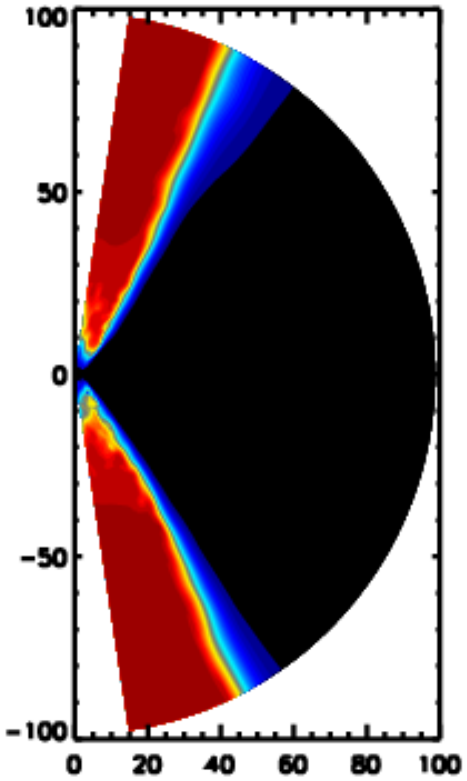
Poynting Flux from Spinning Black Holes



EM Energy Flow: Poynting Flux



Mass Outflow Slower



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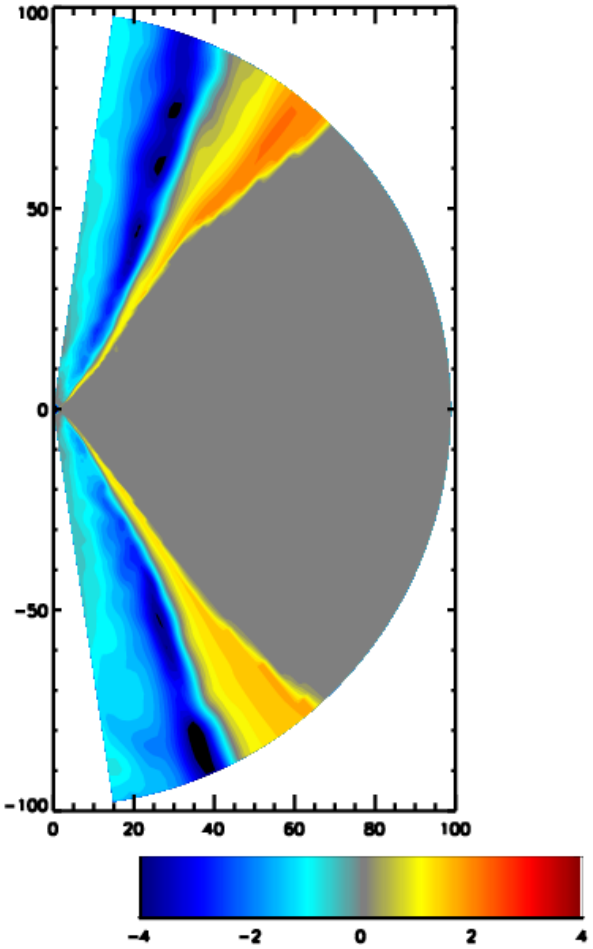
And Constant in Angular Momentum

Retrograde in funnel interior!



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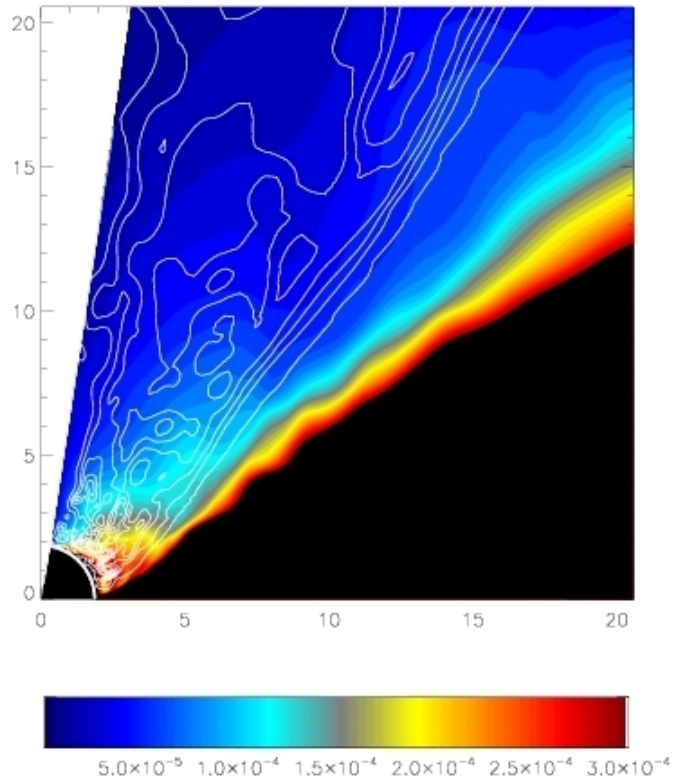
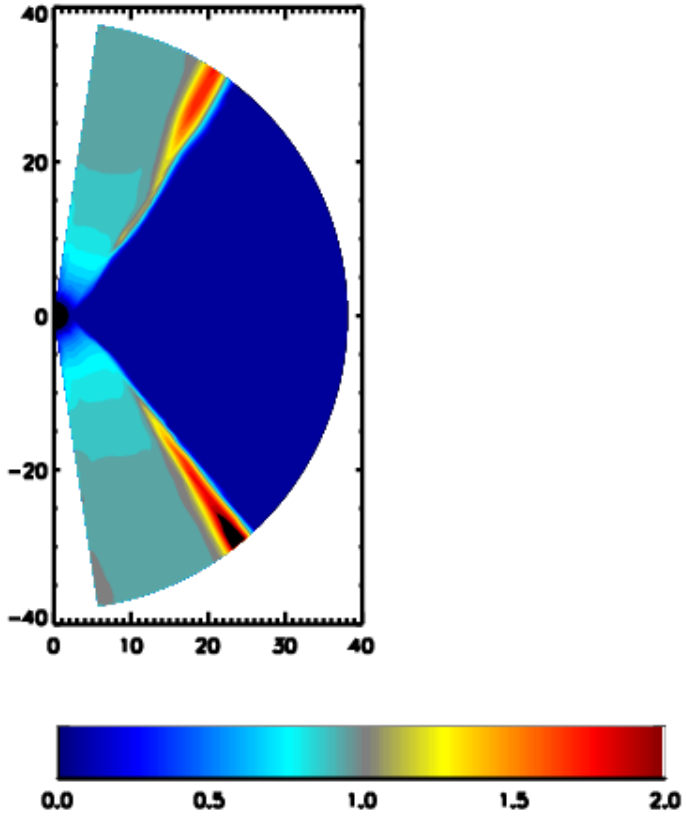
Coronal Pressure Gradients Inject, Accelerate Mass



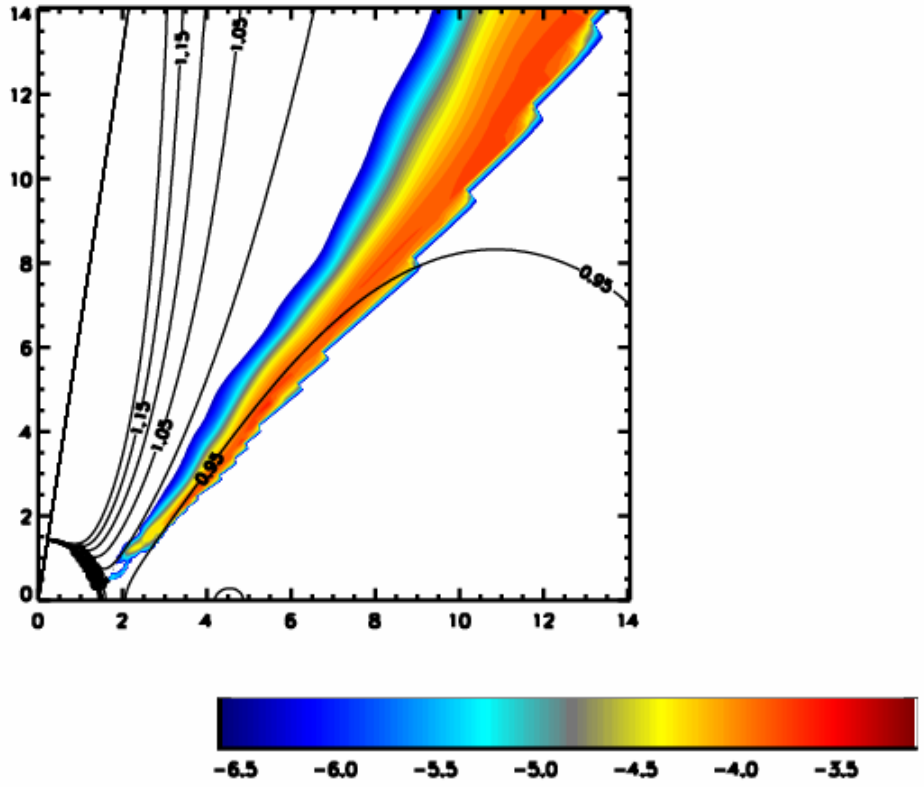
a/M = 0.5



$p_g + B^2/8\pi$ vs. $\rho h u^r u_r$

Magnetosonic Mach number

Collimated by Centrifugal Barrier and Coronal Pressure



Substantial Energy Efficiency for Rapid Spin

$$\eta_x = \dot{E} / \dot{M}^a$$

a/M	η_{matter}	η_{EM}	η_{NT}
-0.9	0.088	0.023	0.039
0.0	0.0022	0.0003	0.057
0.5	0.063	0.0063	0.081
0.9	0.22	0.046	0.16
0.93	0.065	0.038	0.17
0.95	0.13	0.072	0.10
0.99	0.41	0.21	0.26

A Start at Answering Some Questions

Net flux:

Not required for jets, but effects remain to be explored

Magnetic field strength:

From accretion dynamics, spin (plus trapped flux?)

Field structure:

(Rough) prograde helix around black hole rotation axis

Black hole vs. disk:

At least the black hole, when it rotates

Other forces, mass-loss rate:

In *these* circumstances, funnel-wall mass outflow driven by coronal pressure

Summary

- Now possible to do full 3-d GR MHD disk-jet simulations
- With no initial large-scale magnetic field, poloidal field is created in a cone around the axis
- Spinning black holes drive strong outflows
- Matter and EM fields are energetically comparable

More Questions

- External large-scale fields?
- Genuine thermodynamics?