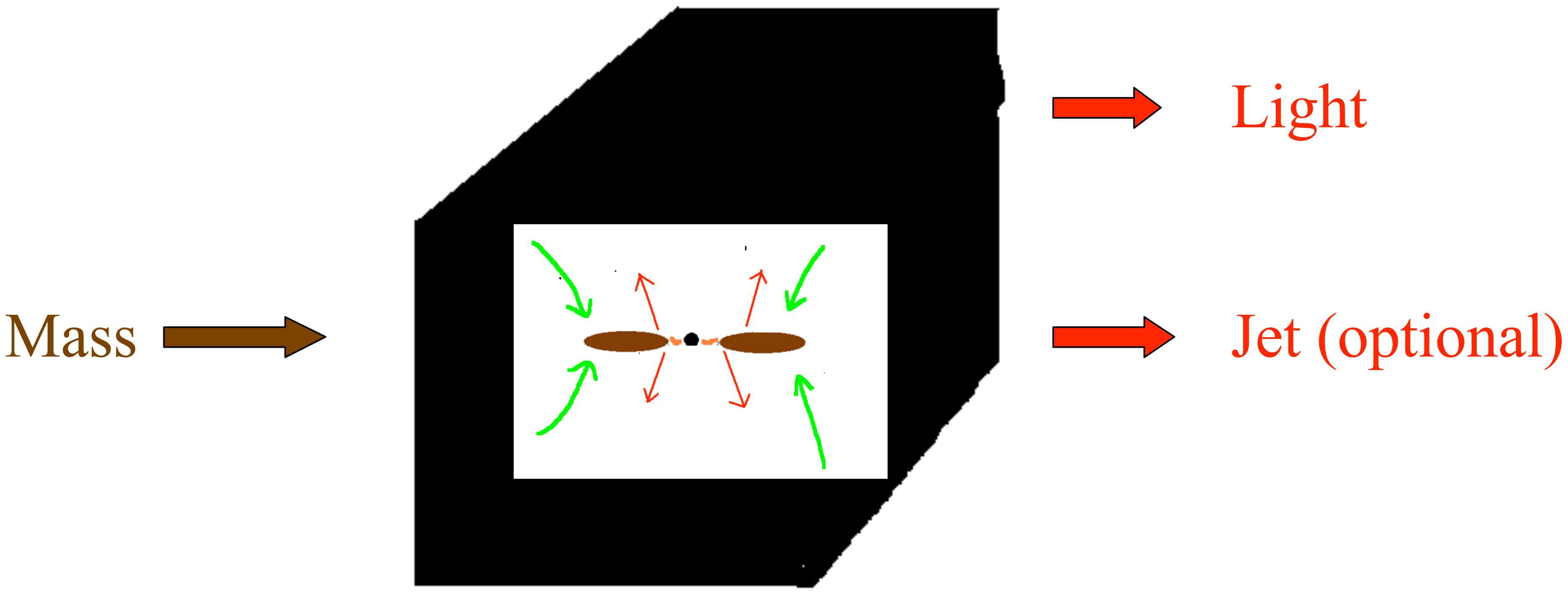
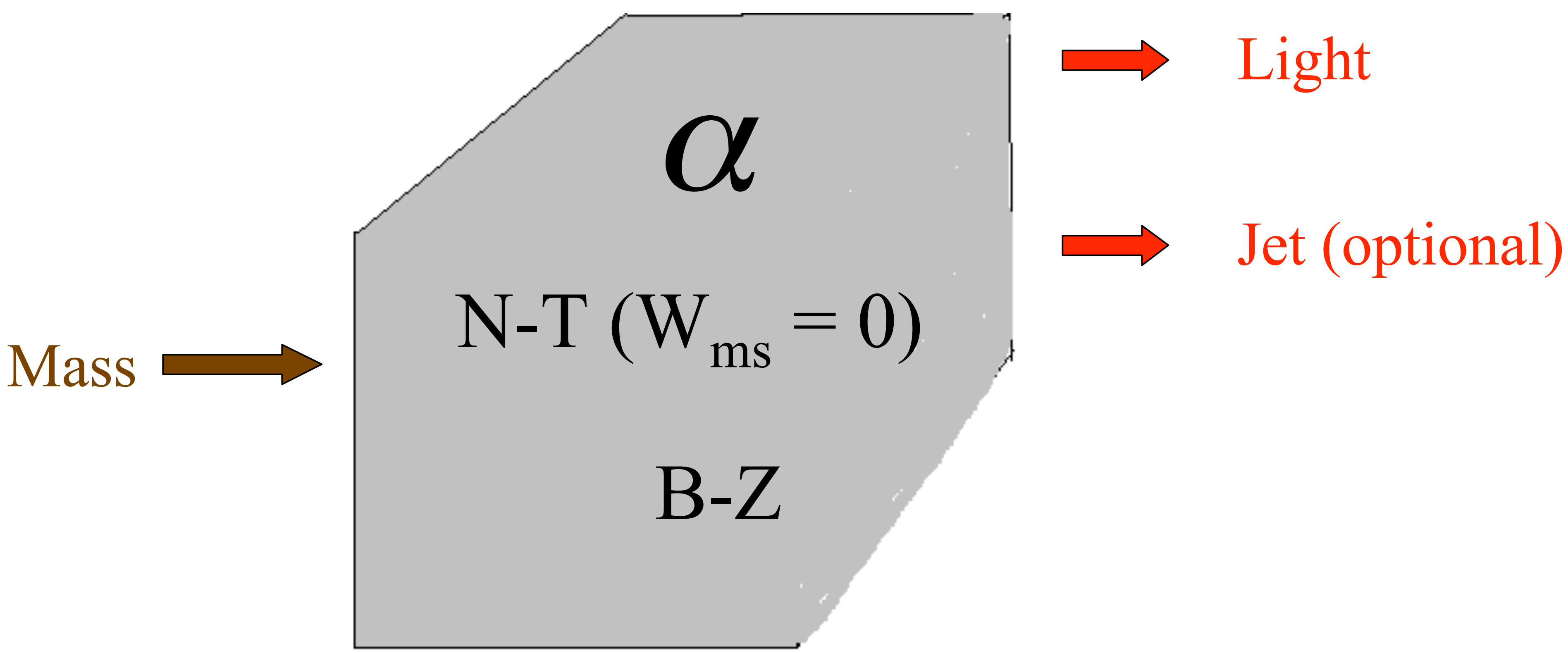
THE BLACK HOLE TAKES AND THE BLACK HOLE GIVES…….

with Kris Beckwith, Omer Blaes, Shane Davis,
John Hawley, Shigenobu Hirose, Scott Noble

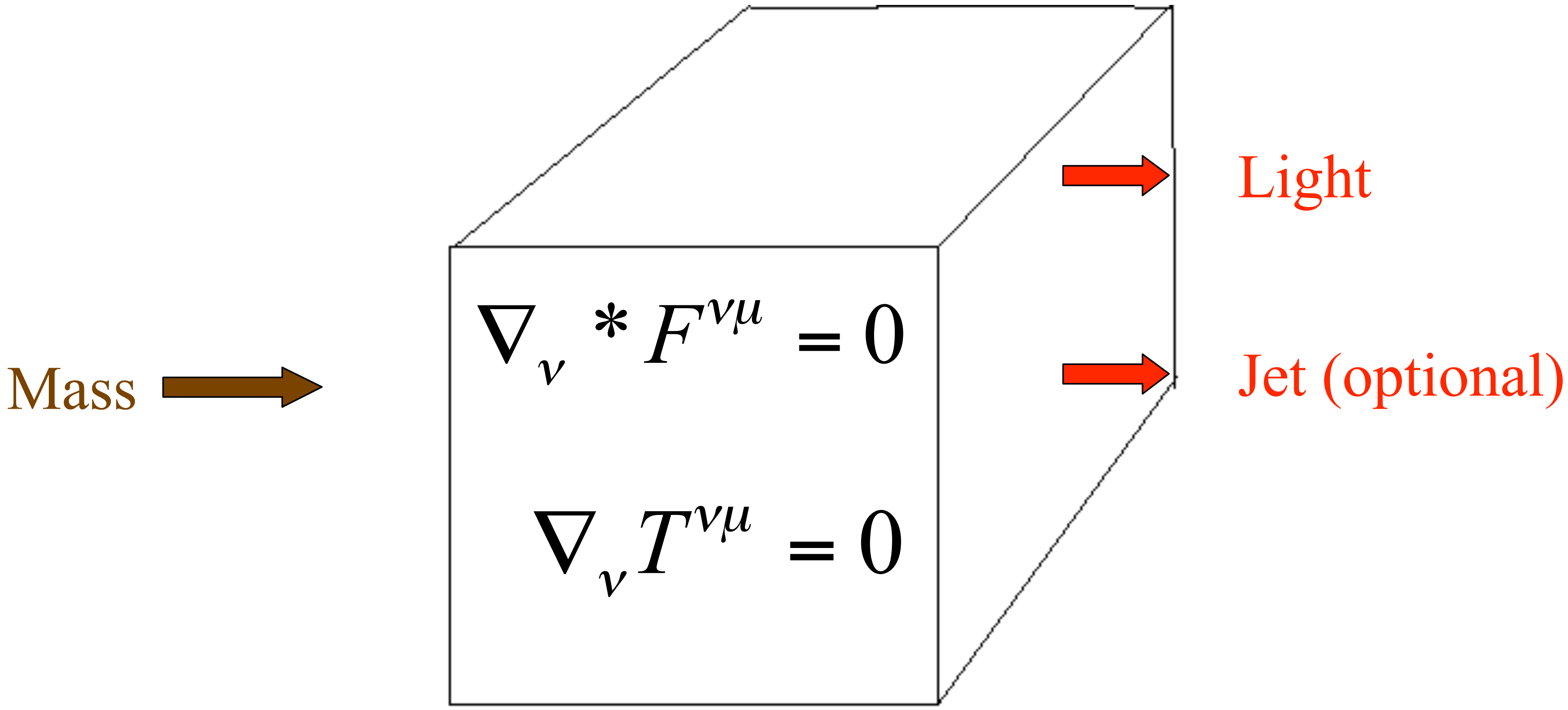
A Central Engine As Some Imagine It



A Central Engine as Others See It



A Central Engine as We'd Like to Understand It



$$\nabla_\nu {}^*F^{\nu\mu} = 0$$

$$\nabla_\nu T^{\nu\mu} = 0$$

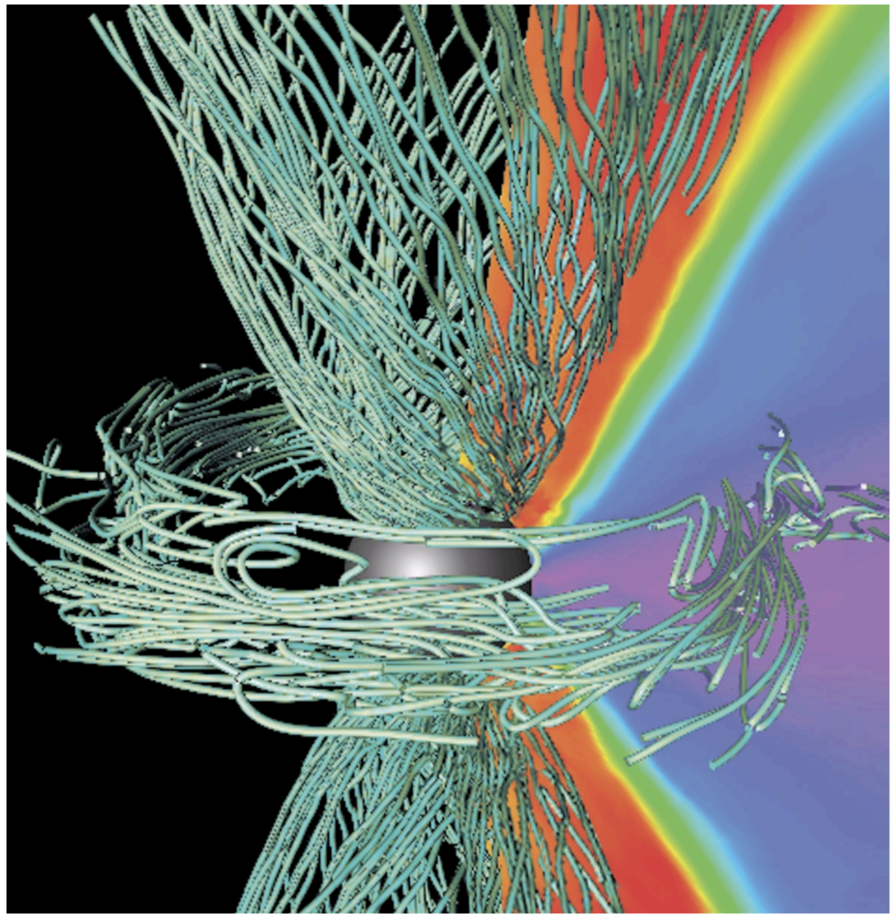
Key Ingredient: MHD Turbulence

Magneto-rotational instability →

MHD turbulence in disk;

(large-scale magnetic field) *or* (inflation of internal turbulent fields) →

relativistic jet



How Exactly Do Outputs Work?

- MHD turbulence dissipates into heat, thence to radiation, but

  radial profile?

  total efficiency → mass budget?

  thermal vs. coronal?

- Jet regulation

  black hole spin?

  magnetic field?

Essential Device: Numerical Simulation

- Stratified shearing-boxes

  "rectangular" annular segment

  study turbulent cascade; radiation transport, forces

  Newtonian, ideal MHD, real EOS, flux-limited diffusion

- Global disks

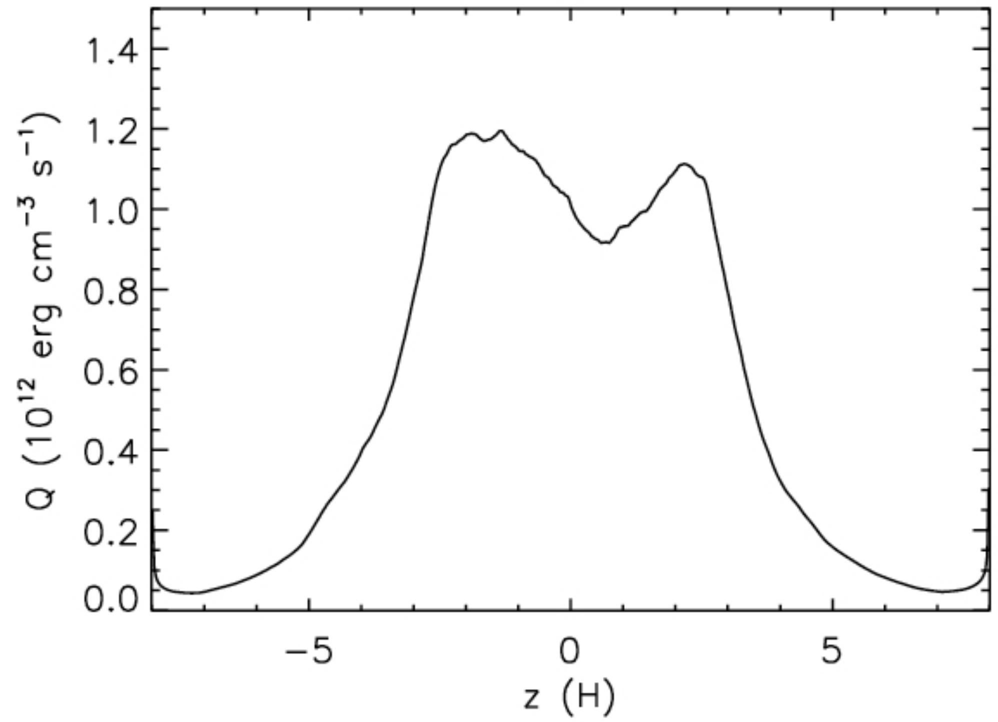
  study global structure, radial gradients, jets

  full GR in Kerr metric; primitive thermodynamics

Disk Dissipation and

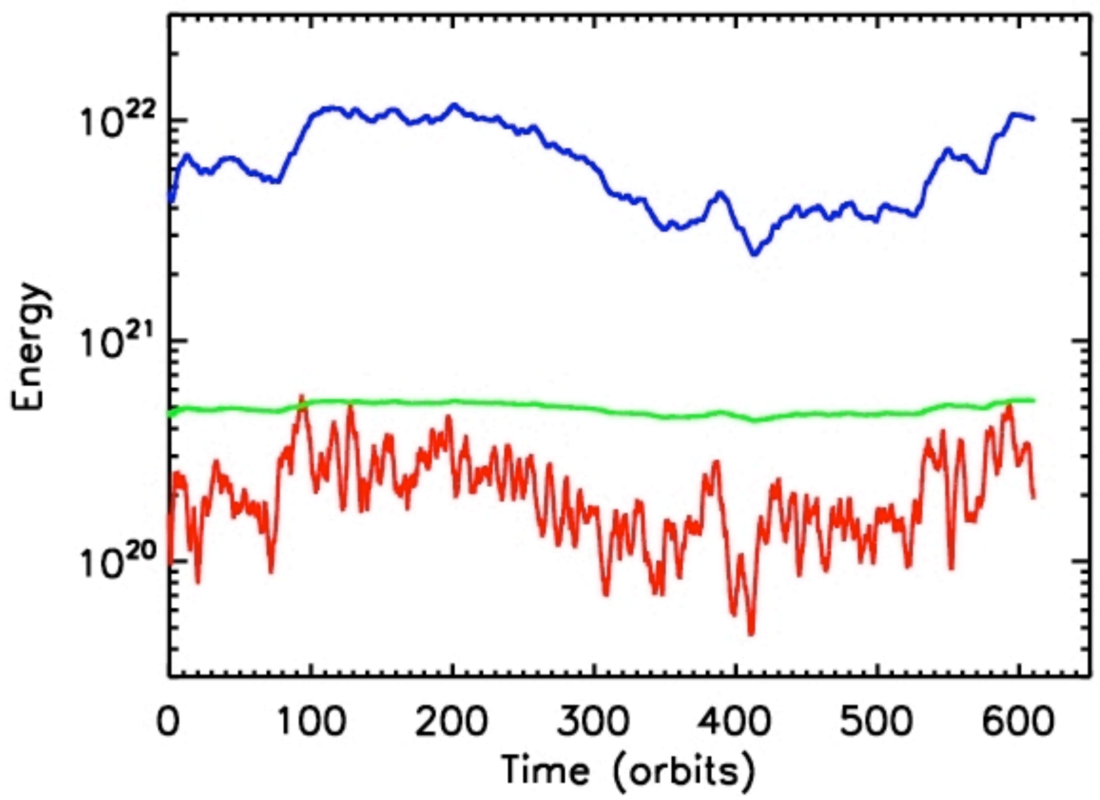
Total Radiative Output

Dissipation: Time-Averagd Local View



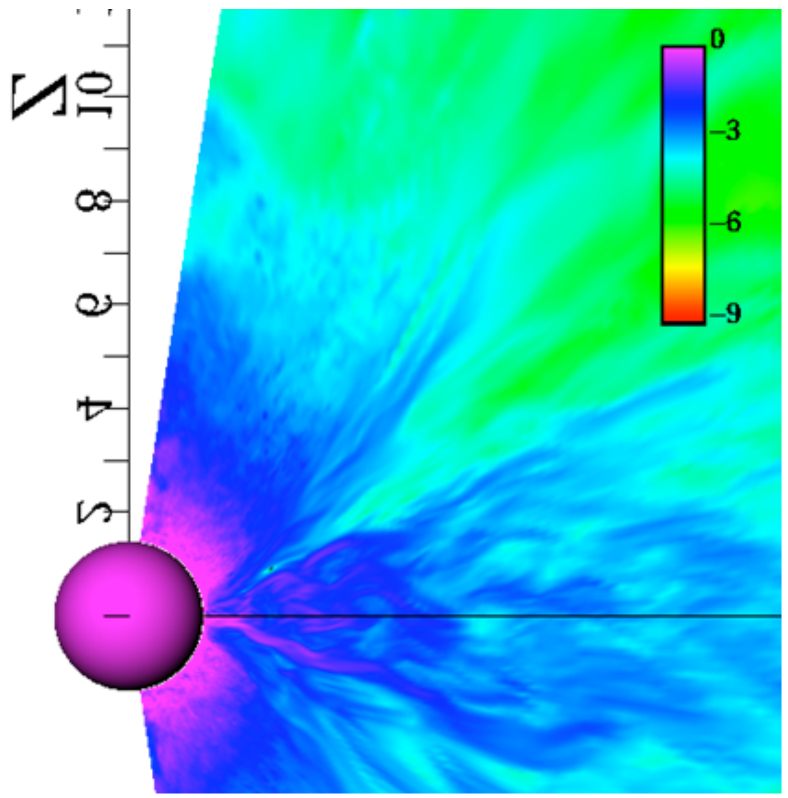
Magnetic reconnection, shear viscosity, shocks

Turbulence Makes Local Energy Content Fluctuate



t_{cool} = 15 orbits

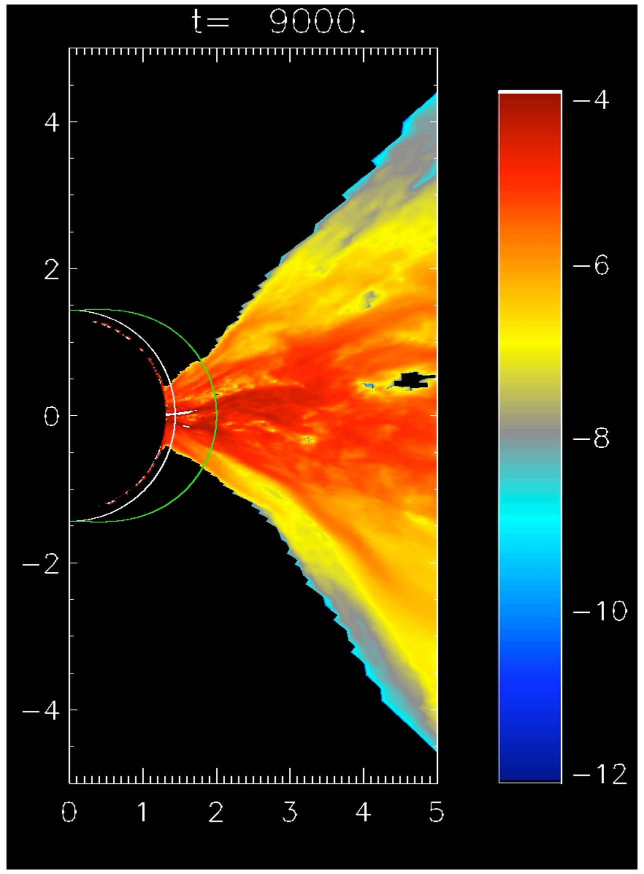
Dissipation: Global View



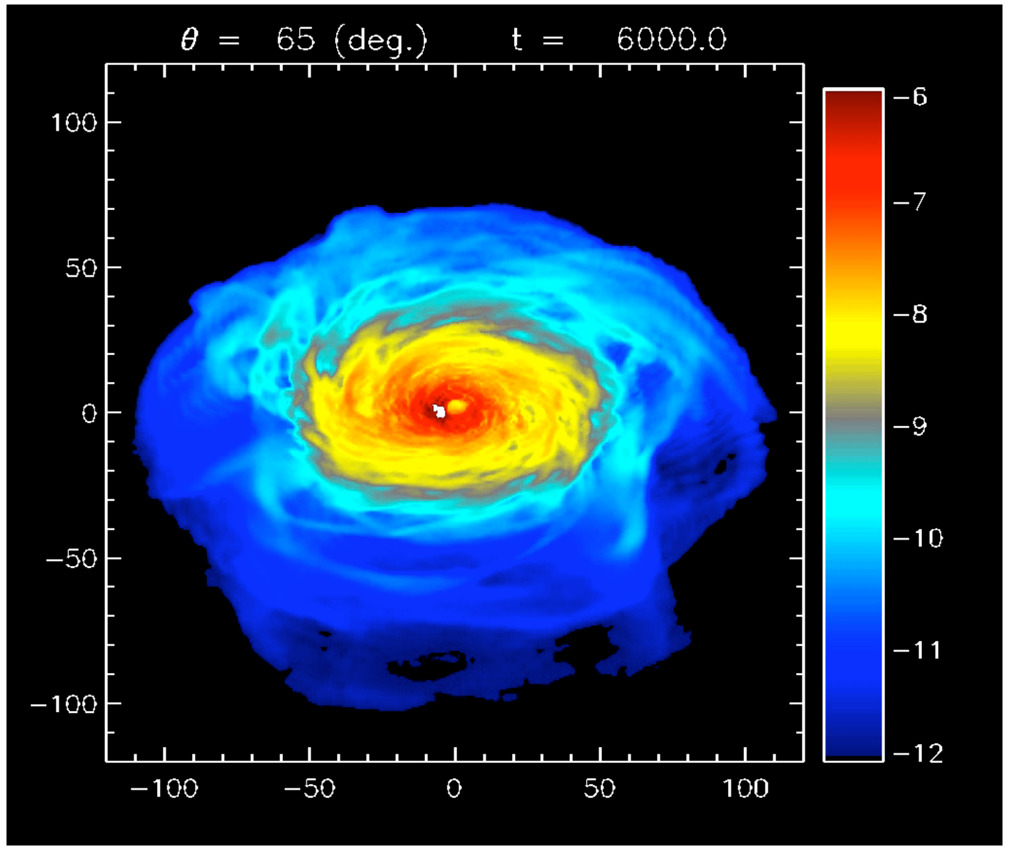
A proxy: $|J|^2$

Dissipation: Another Global View

Bound matter only, toy-model cooling function

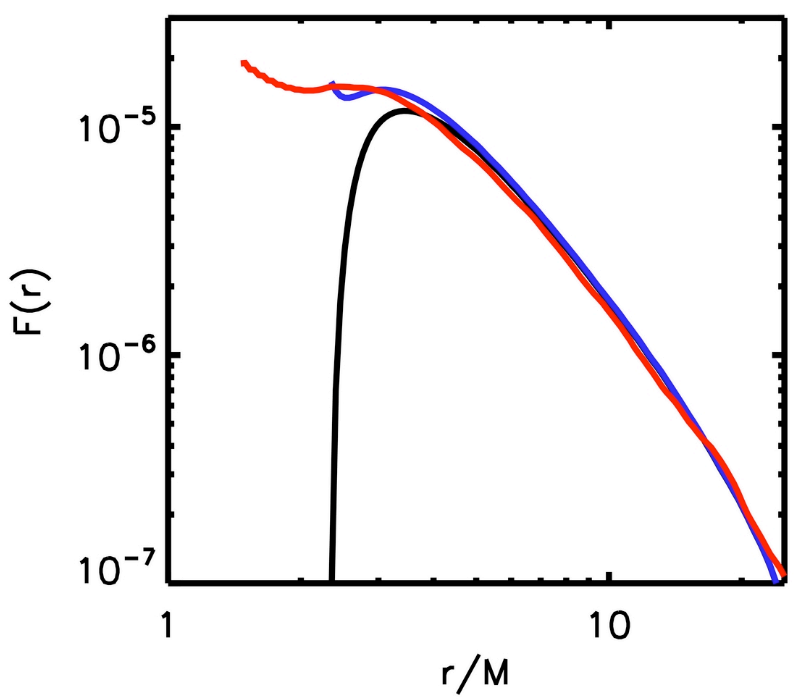


fluid-frame emissivity

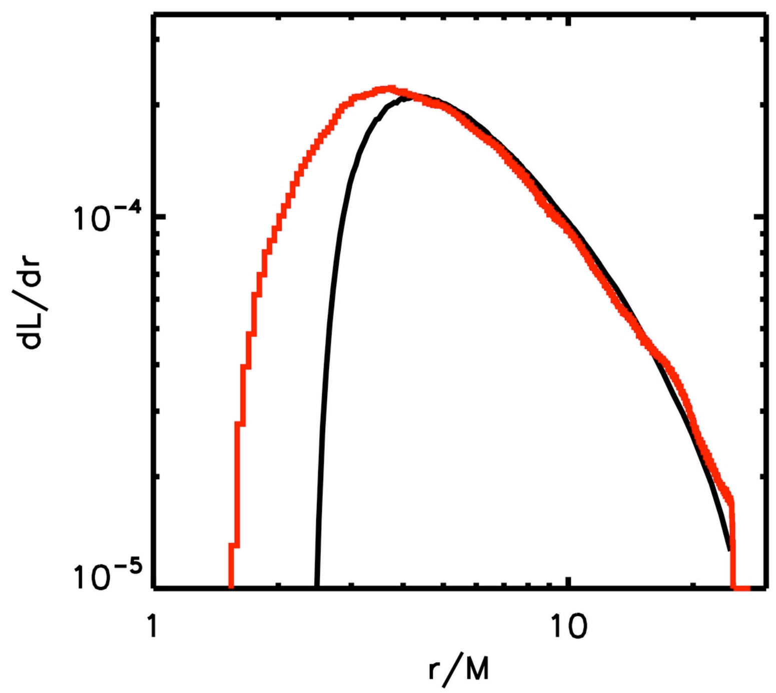


full GR ray-tracing, Doppler shifts

Time-Average Emissivity Radial Profile



fluid-frame surface brightness

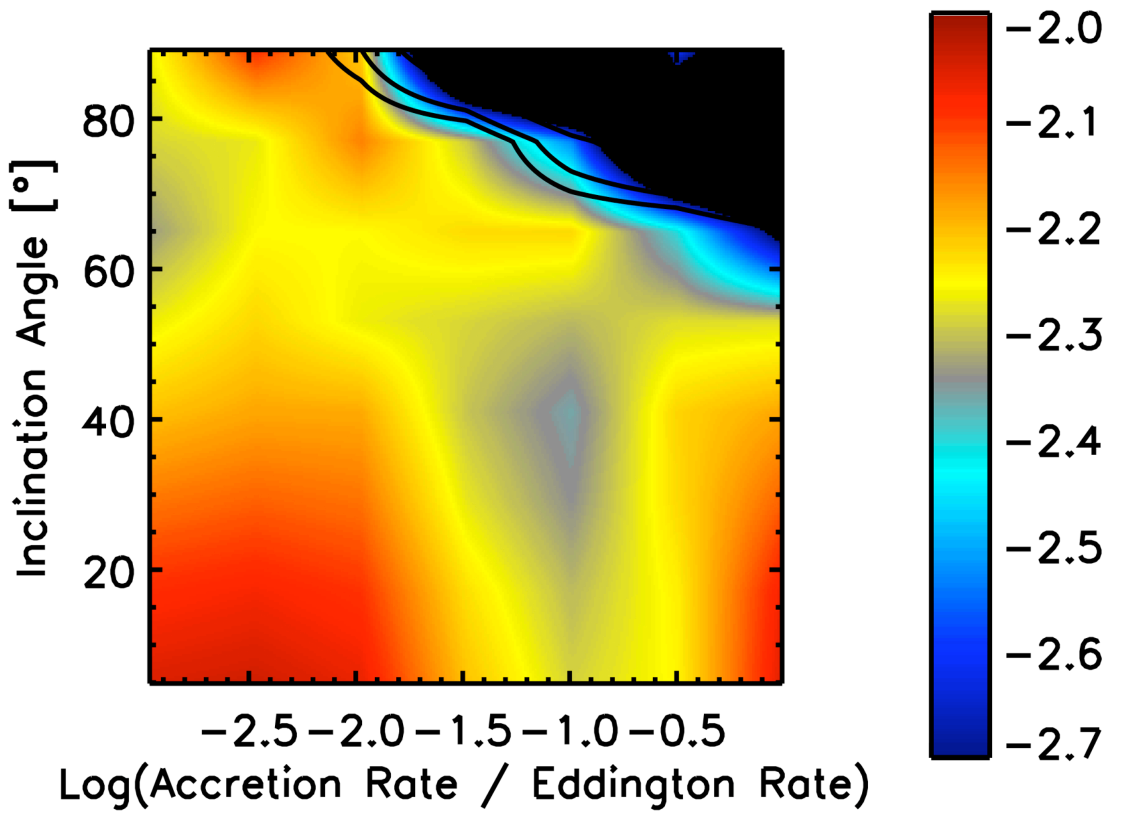


luminosity at infinity

Light-Curve Fluctuations

Cooling function model is optically-thin→

focus on coronal part



Result: power-law power spectrum, index ~ -2

Total Efficiency

Novikov-Thorne nominal efficiency for a/M = 0.9: 0.155

N-T after photon capture, Doppler shifts: 0.143

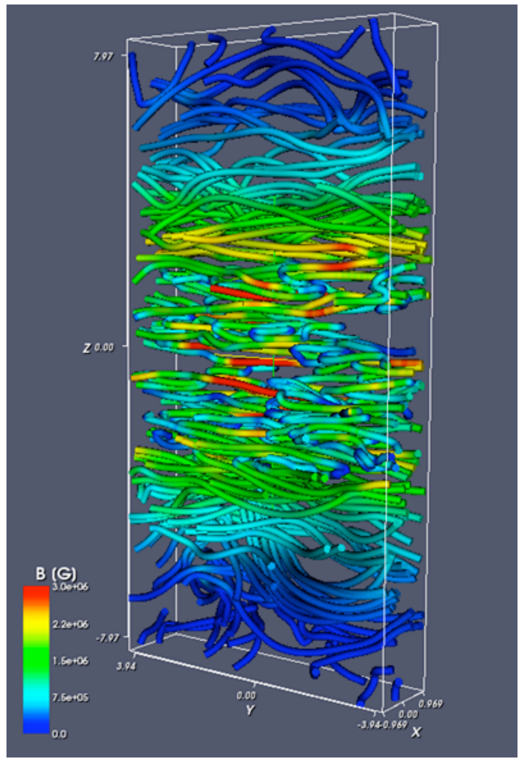
Explicit calculation for a/M = 0.9, with photon capture,
Doppler shifts: 0.151

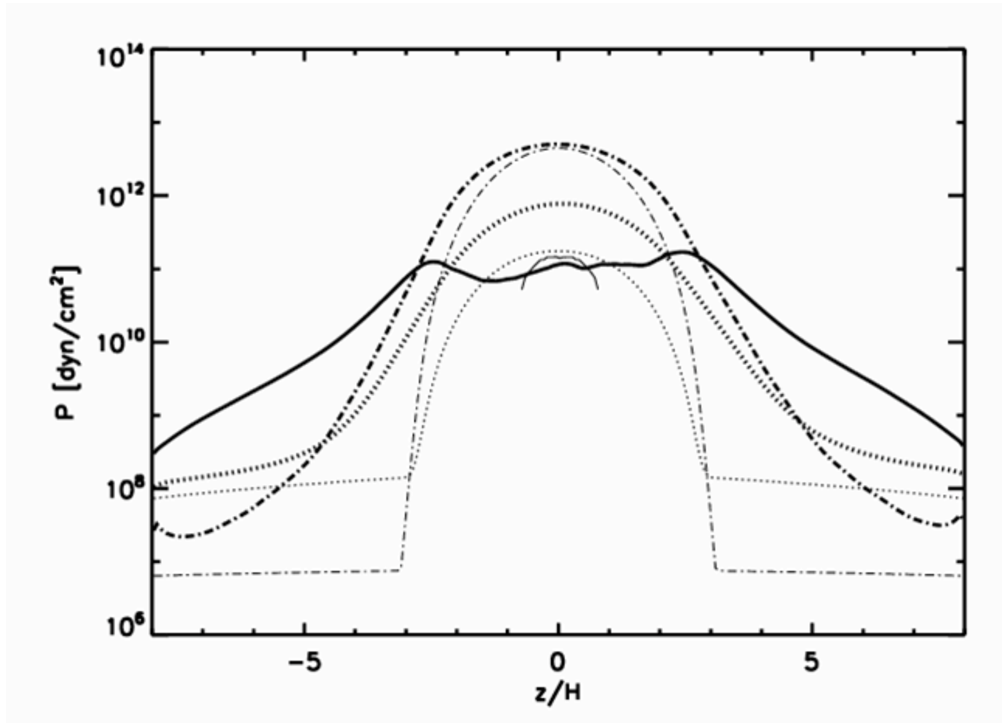
Unradiated heat at ISCO: 0.02

Magnetic energy/rest-mass at ISCO: 0.03

Disk Structure and Emitted Spectrum

Thermal Spectrum: the Disk Atmosphere

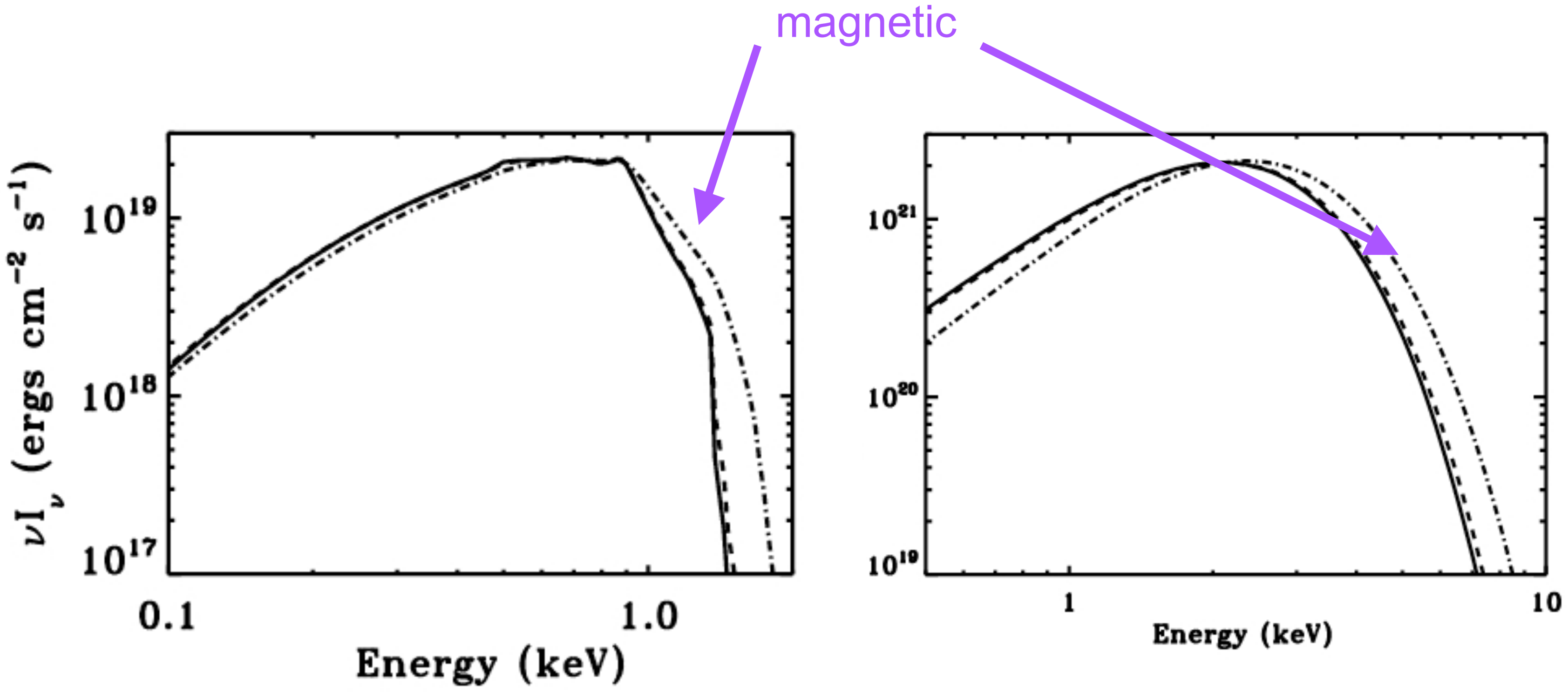




Midplane always turbulent, pressure-dominated;
corona always laminar, magnetically-dominated

Magnetized Corona Alters the Photosphere

Atmosphere depends on T_{eff}, g; magnetic support increases g, decreases gas density

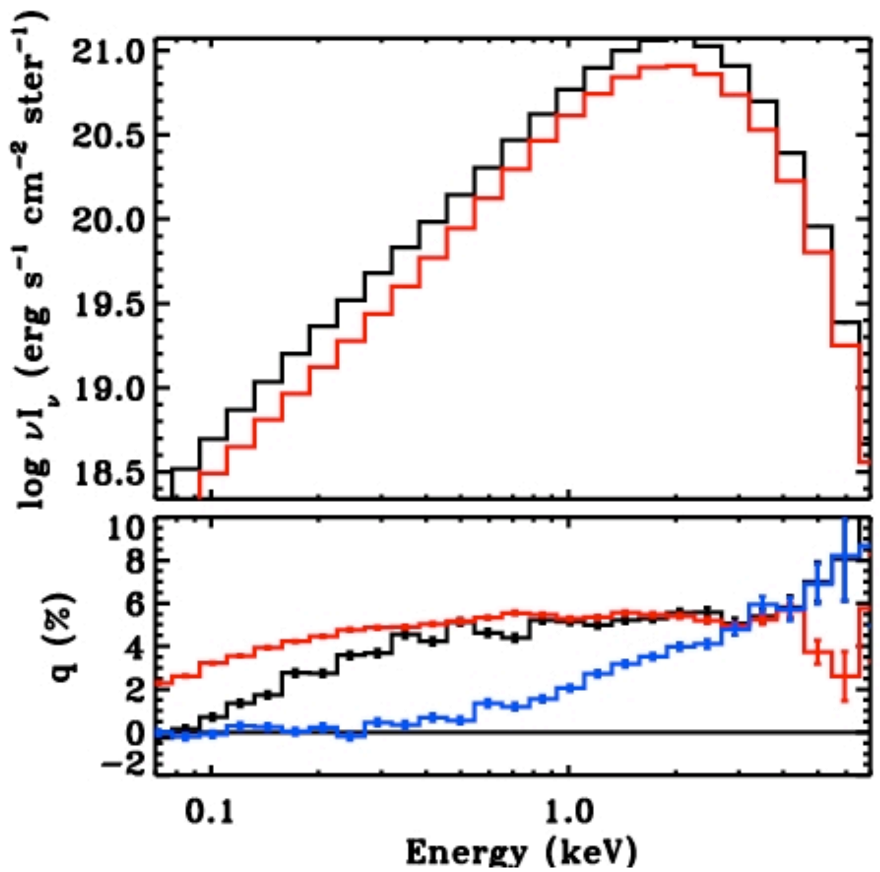


r/r_g=300

r/r_g=30

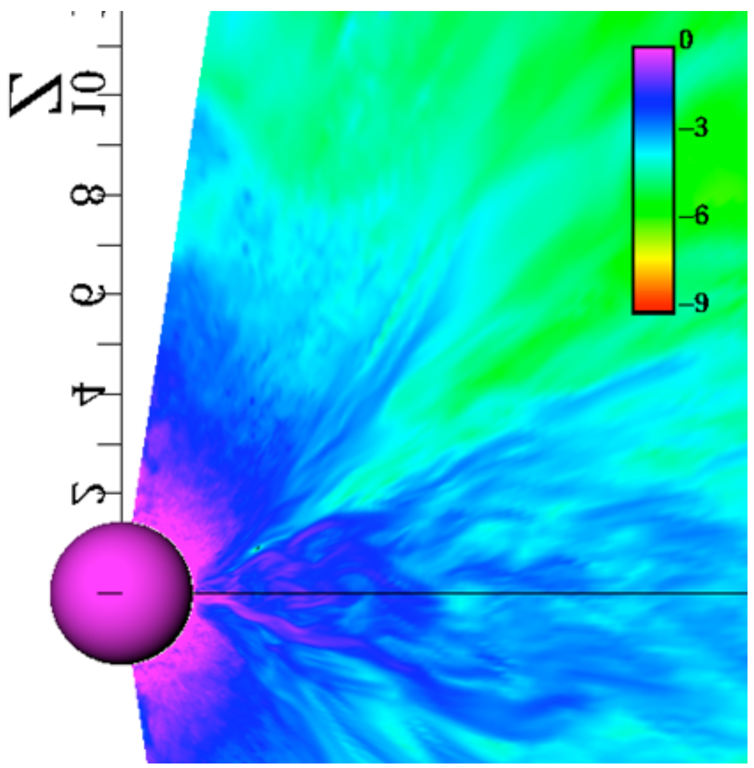
Specific parameters appropriate to stellar-mass black holes, not AGN

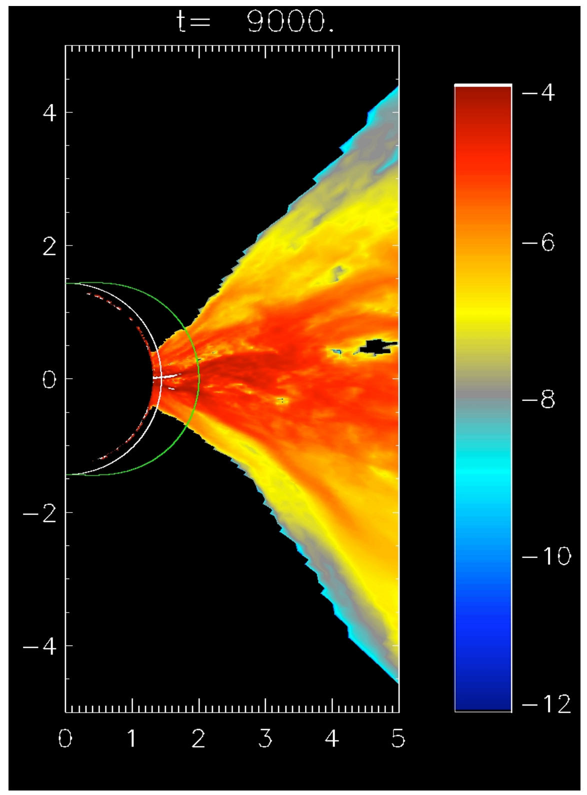
Magnetized Corona Alters Polarization



Fluctuations in Faraday rotation
wash out polarization

Where is Coronal Heating Strong?





Implications of Detailed Coronal Data

Known heating rate, location, velocity →

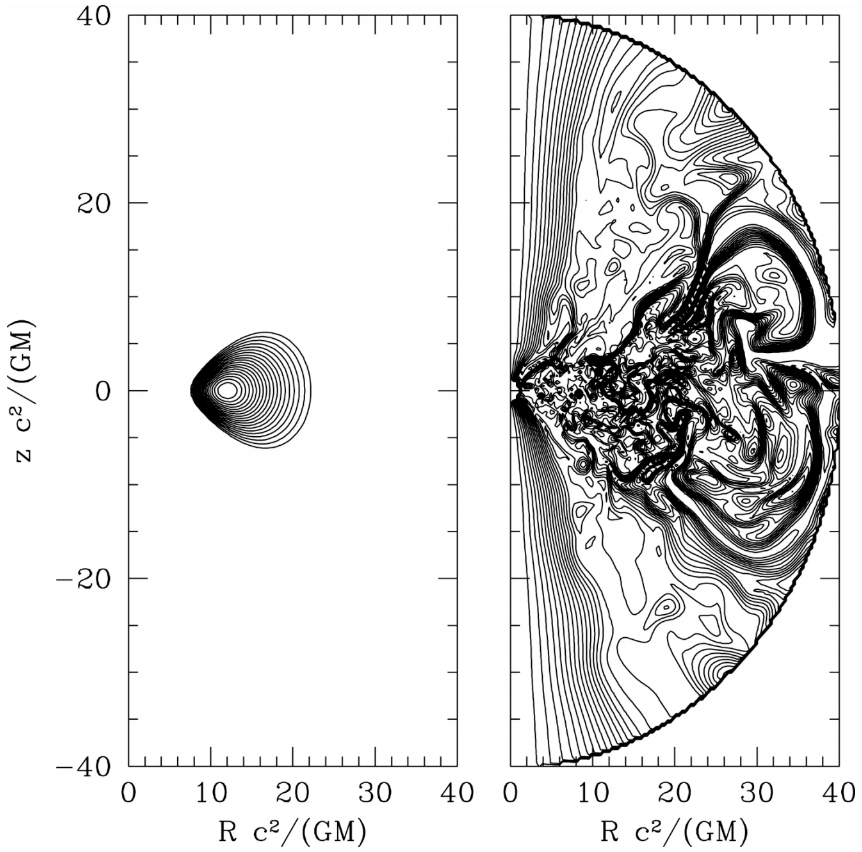
physically-based prediction of hard X-ray emissivity, illumination of disk

Disk Physics – Light Output Connections

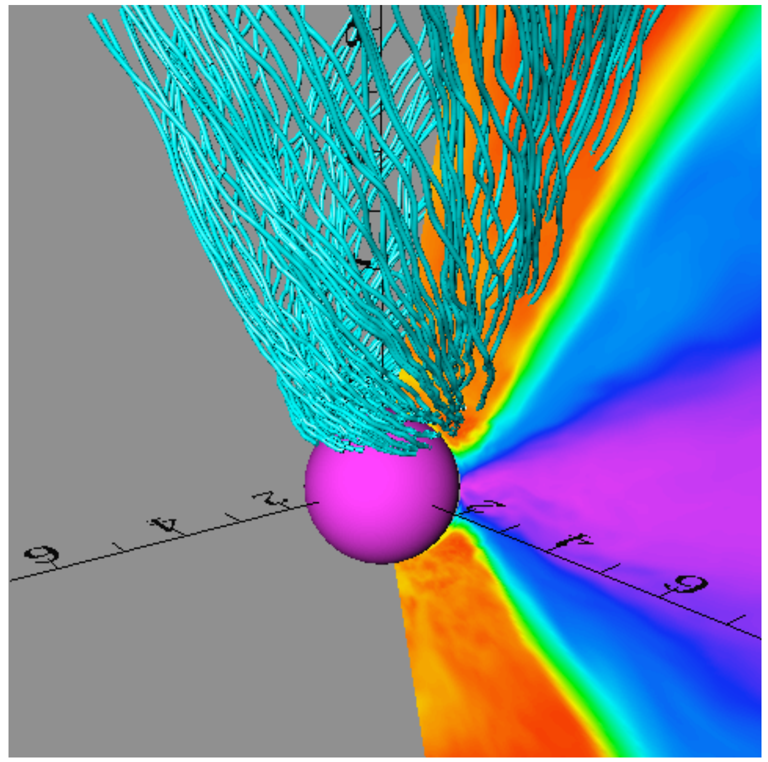
- Departures from LTE in time-averaged thermal spectrum
- Higher characteristic temperature than traditional predictions
- Power-law power spectrum of coronal fluctuations
- Location and motion of sources for coronal photons? → predict Fe Kα profile
- Less mass required for emitted energy

Jets

Large-Scale Field Arises Spontaneously from Small-Scale Dipolar Field

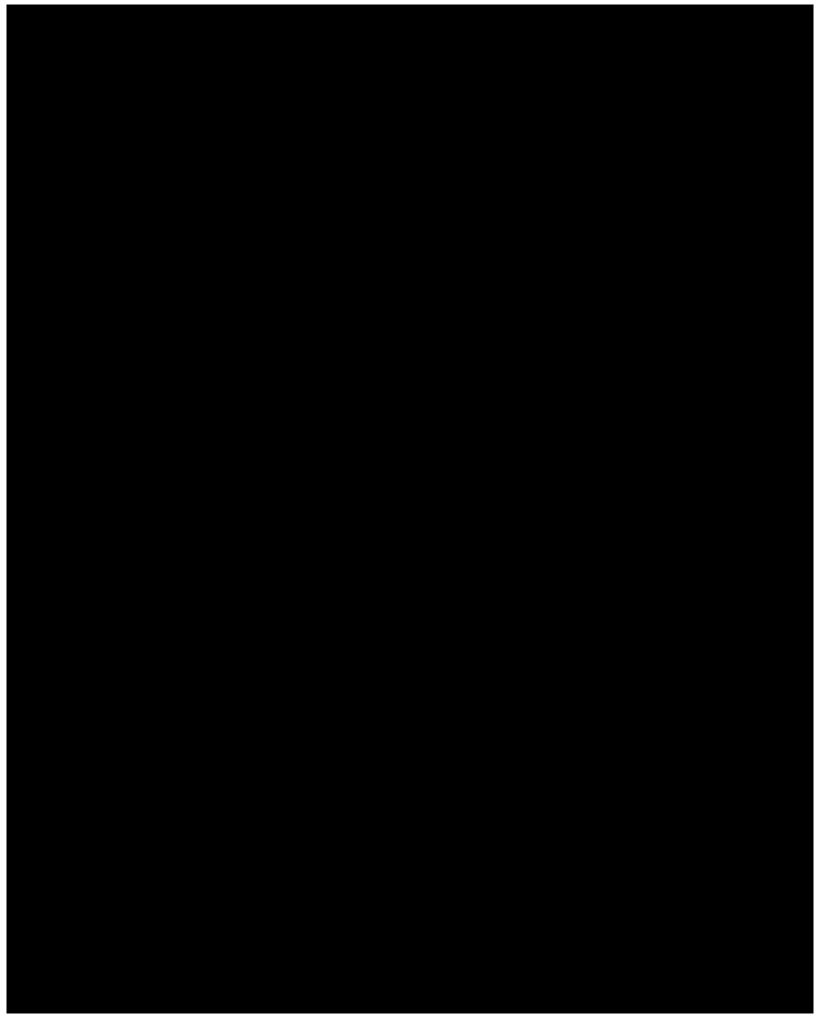


McKinney & Gammie 2004



Hirose et al. 2004

Jets Can Be Strong and Variable



Cf. Blandford & Znajek 1976;

McKinney & Gammie 2004

Significant Energy Efficiency from Internal Dipole Field with Rapid Spin

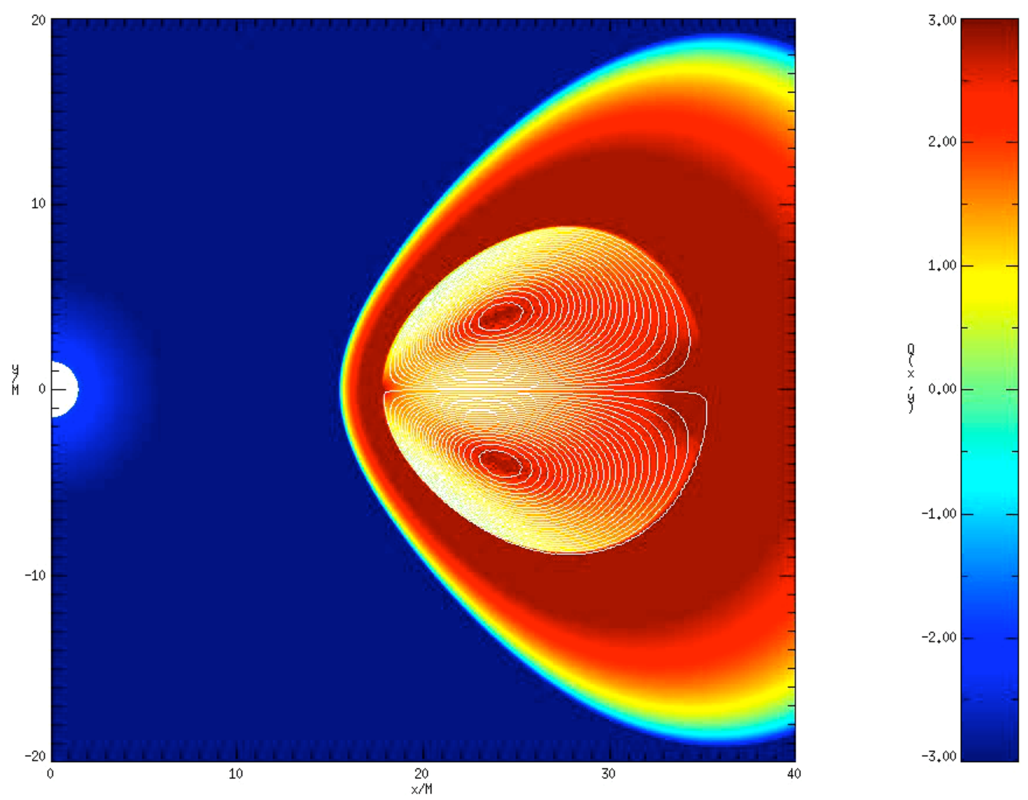
$$\eta_x = \dot{E} / \dot{M}_{acc}$$

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	0.18
0.99		0.21	0.26

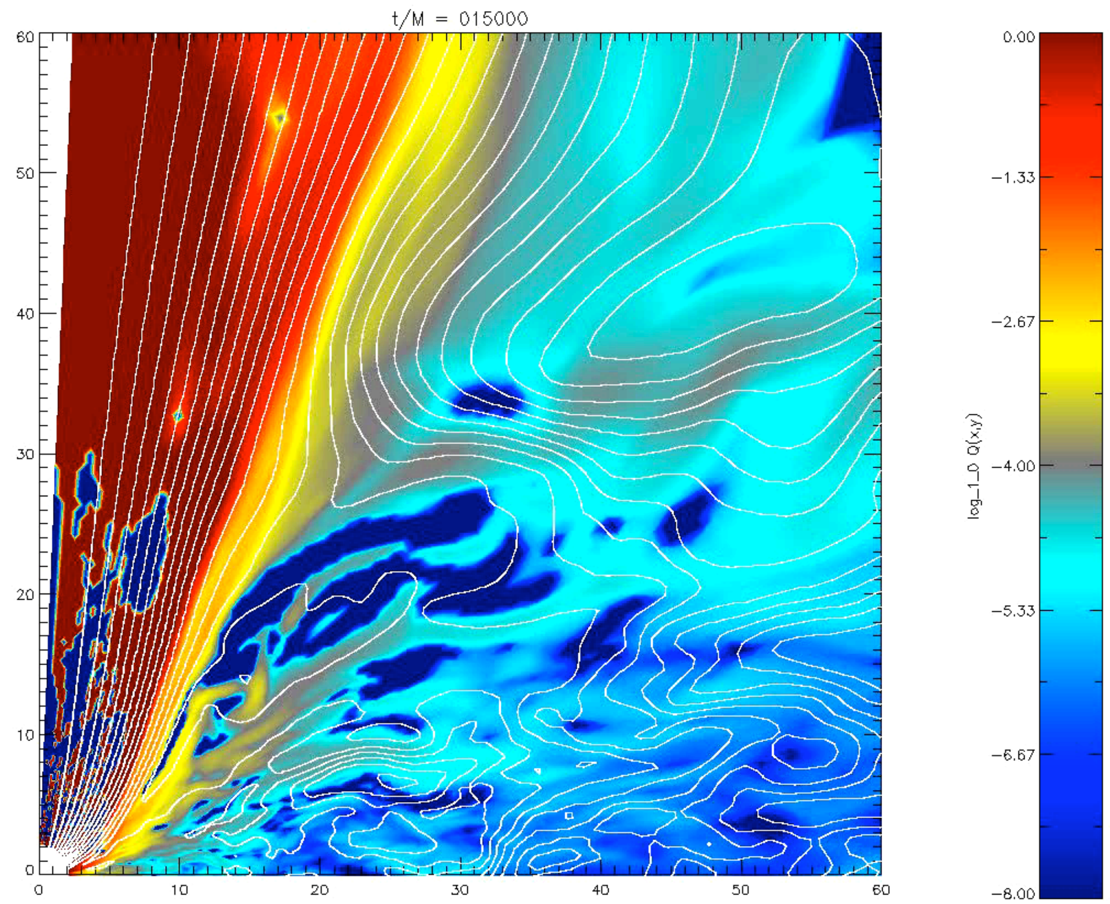
But Field Geometry Matters

Quadrupolar (or smaller dipolar loop) field geometry makes reconnection easier, leading to episodic, overall weaker jets

Rule-of-thumb: vertical field must retain a consistent sign for at least ~1500M to drive a strong jet



Large-scale Magnetic Flux Accumulated Non-Diffusively



Implications for Jet Output

Jet power controlled by:

- black hole spin
- internal field topology
- history of large-scale field feeding/disk pressure

Summary

- MHD simulations adding much to physical understanding of central engines
- And also potentially to understanding their outputs:

    shape of thermal disk spectrum

    strength of coronal emission

    disk illumination

    variability

    accretion efficiency

    jet strength