Tilted Disks around Black Holes: Investigating the Alignment Mechanism

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I use Blue Waters for the capstone simulations in a series of numerical experiments that probe the mechanisms by which external torques align accretion disks

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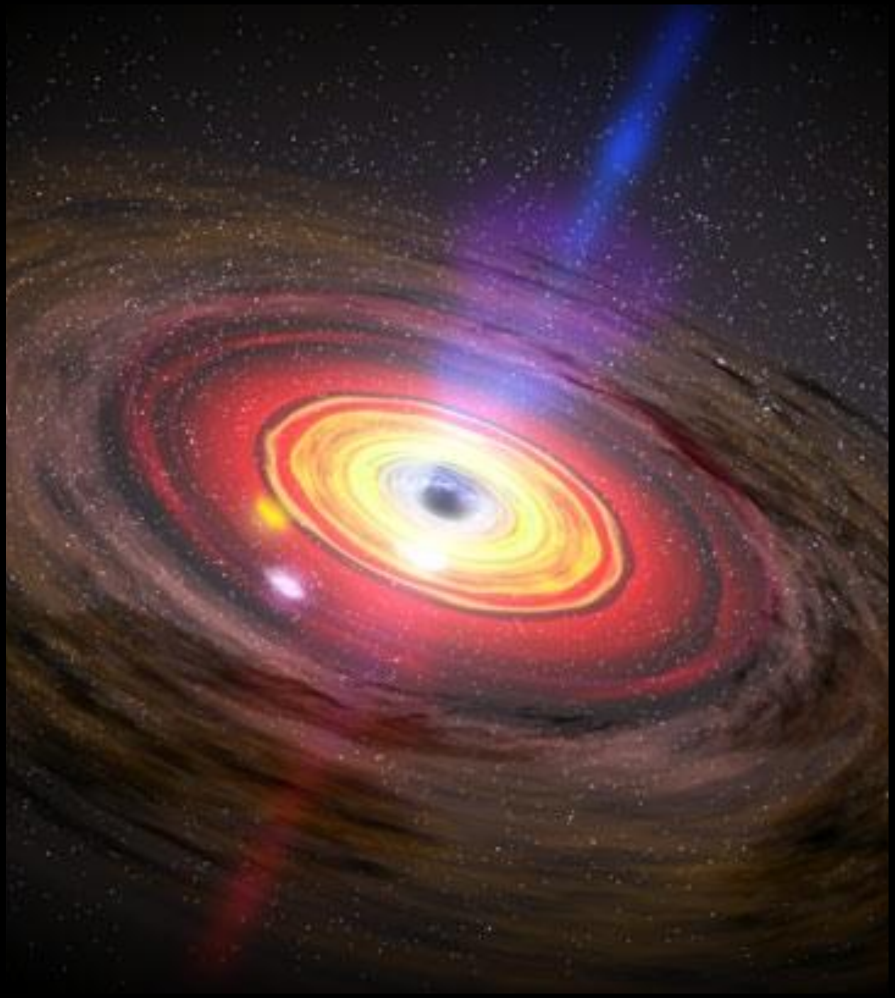
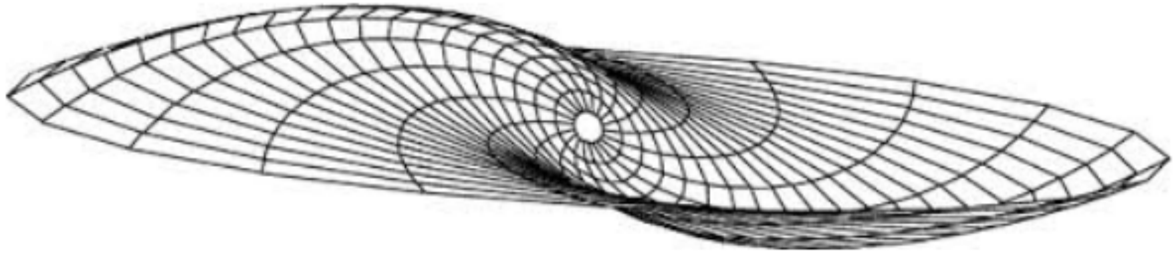
Accretion Disks in Astrophysics



- Gravity + angular momentum
- Quasars, active galactic nuclei, black holes, neutron stars, white dwarfs, proto-stellar and proto-planetary systems
- Basic concepts are understood, but details are complex and observations difficult

Disks may be tilted and twisted

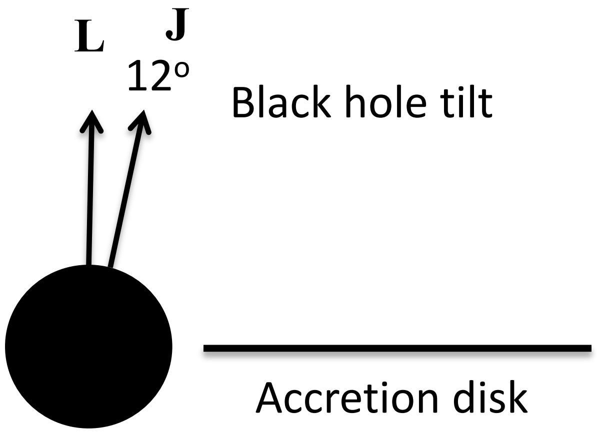


- Multiple angular momentum vectors: disk, central star (black hole) spin, orbital angular momentum of binary
- No necessary reason for these to be initially aligned
- Do they become aligned? If so, at what radius? (Implications for observations, jets, etc.)

Tilts Make Torques

Rotating solitary mass: $\mathbf{T} = 2(G/c^2)\mathbf{J} \times \mathbf{L}/r^3$

$$\Omega_{\rm prec} \sim (c/r_g)(r/r_g)^{-3}$$



- **Differential precession** induced by torques
- *Dissipation* between neighboring rings leads to alignment
- Questions remain regarding mechanisms of alignment and location of alignment transition, *nature of dissipation*

Key Challenge: Dissipation and Disk Alignment

- Dissipation between rings is key to alignment. But what is the nature of that dissipation and how does it work?
- Most analytic (and many numerical) studies of disk alignment have made use of the ”alpha viscosity” parameterization, assuming the presence of an actual viscous stress
- $\alpha c_s H = \nu$ Viscosity parameterized as proportional to sound speed times scale height
- Assumption made that a low *Re* viscous disk is equivalent to a high *Re* turbulent disk
- Generally treated as an isotropic viscosity
- **However:** The source of accretion *stress* is MHD turbulence driven by the magneto-rotational instability. The (r,ϕ) component of the stress tensor is strongly favored by the MRI
- “*A large-Reynolds-number turbulent disk is simply not a laminar disk with a much smaller Reynolds number*.”
- Existing analytic theory is, at best, suspect.

This Investigation

- No assumed viscous stress; MRI-driven MHD turbulence provides internal stress (no viscosity except bulk viscosity)
- ***Numerical experiments*** on an idealized problem – include/exclude various terms, adjust parameters for contrast
- MHD models are contrasted with pure hydrodynamic models with no accretion stress
- Simplified gravity: Newtonian potential and post-Newtonian external torque term
- Aim: Elucidate physical processes involved in disk alignment through numerical experiments
- First study: effect of sound speed (temperature) and tilt angle of black hole with respect to accretion disk

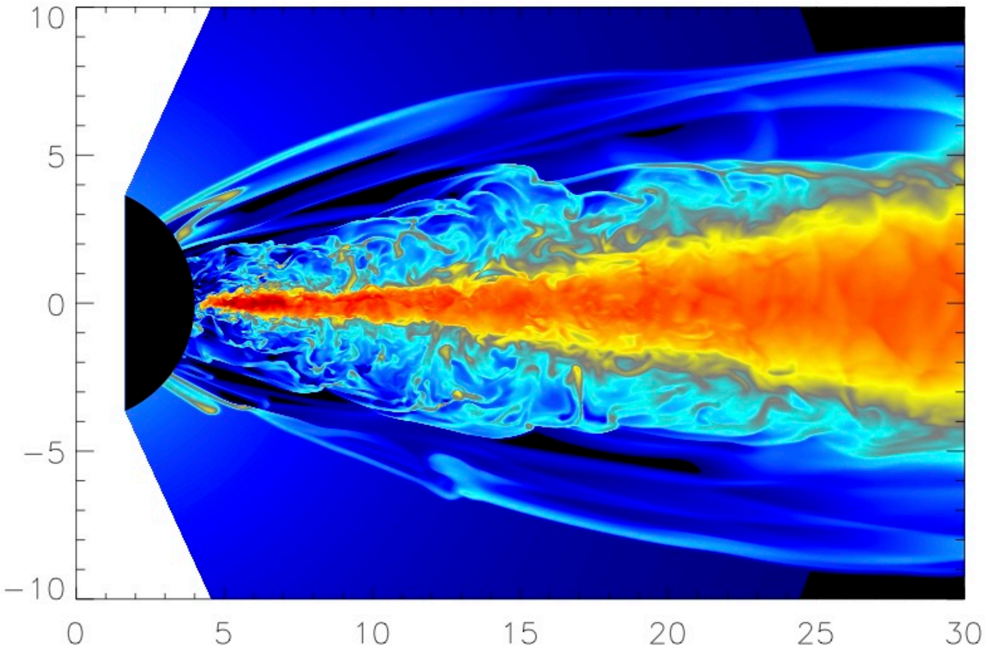
Numerical Approach

- Time-explicit, operator-split, finite-difference compressible MHD ("constrained transport") in spherical coordinates (*ZEUS* algorithm)
- Domain decomposition, MPI parallelization, minimal global communications, excellent weak scaling
- Newtonian gravity with lowest order post-Newtonian terms to account for torque
- Isothermal equation of state to isolate effect of sound speed on alignment. Set of three sound speeds and three tilt angles studied

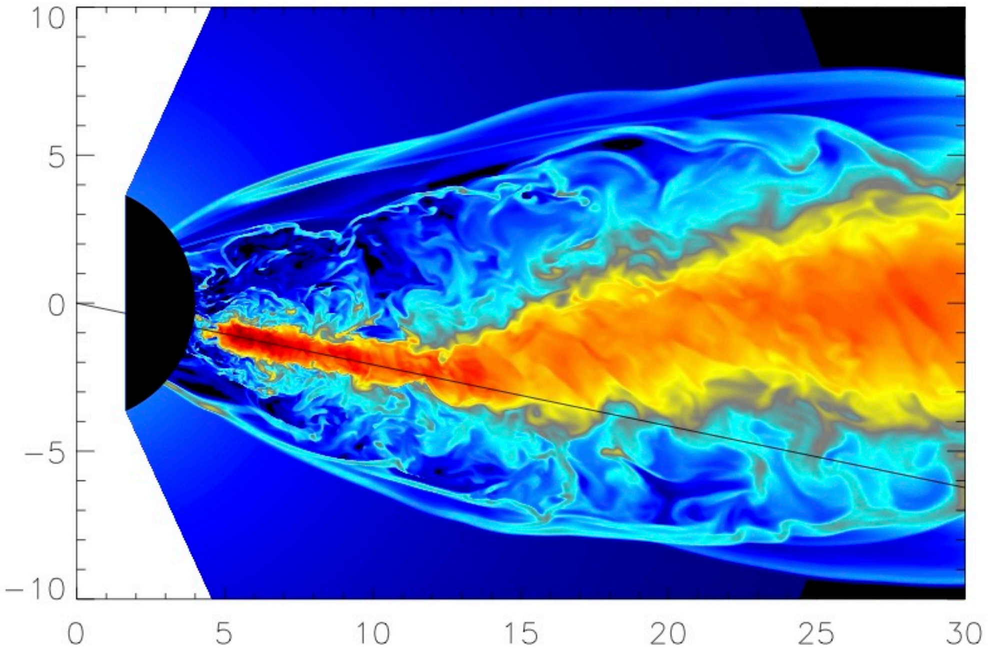
Why Blue Waters?

- Investigation involves Three-dimensional, time-dependent turbulent MHD simulations
- Multiple timescales: Orbital frequency $\Omega \propto r^{-3/2}$; Precession frequency $\Omega_p \propto r^{-3}$; Sound speed over scale height c_s / H ; Alfven speed v_a
- Multiple length scales: Black hole radius, accretion disk extent, pressure scale height H (should be << r), turbulent eddy size (<< H)
- Limit these scales through problem definition; but still require high resolution, long time duration simulation
- Lower resolution simulations, hydrodynamic comparison simulations, etc. can be done on university cluster (order few hundred cores)
- Thinner (colder) disks require greater resolution, as do larger tilt angles
- Capstone simulations require Blue Waters, long running times, ~600M grid zones
- Blue Waters provides the peak of the HPC ecosystem

Lense-Thirring and Disk Alignment

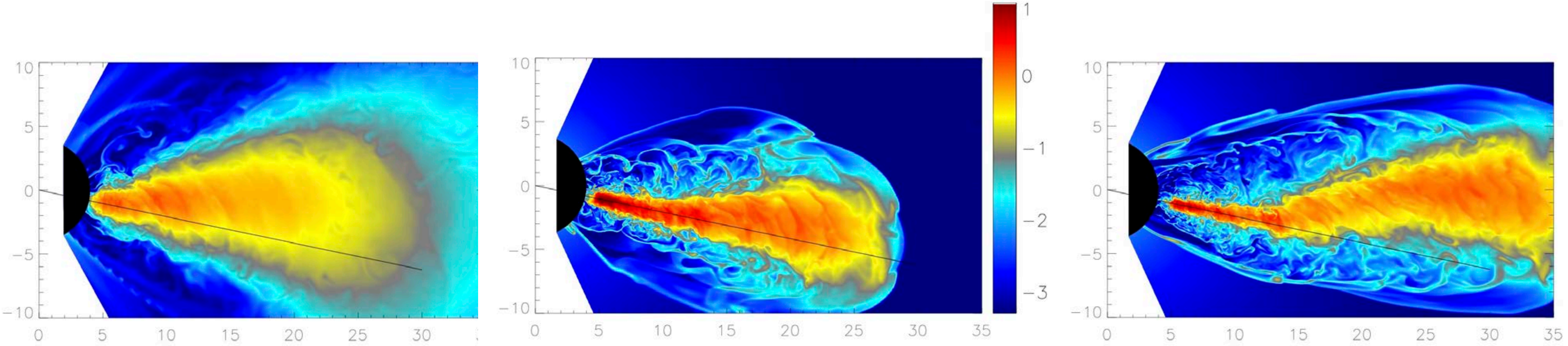


MHD turbulent disk without torque



MHD turbulent disk after 15 orbits with torque

Three Isothermal Disks
12 degree tilt, 3 soundspeeds



Isothermal Keplerian Disk
H/r ~ 0.1 (Krolik & Hawley 2015)

(352x384x1024)

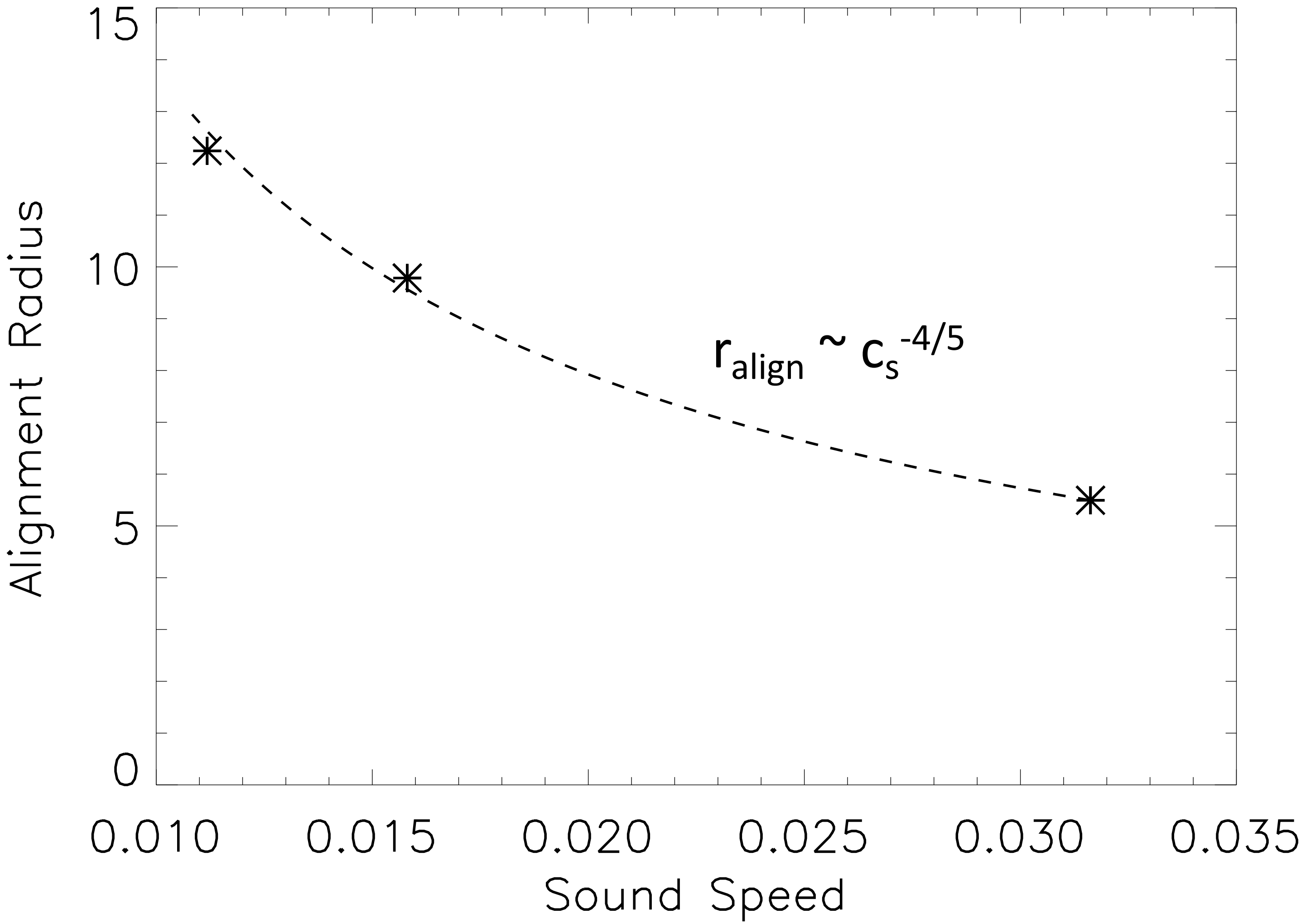
Isothermal Keplerian Disk
H/r ~ 0.05

(704x770x1024)

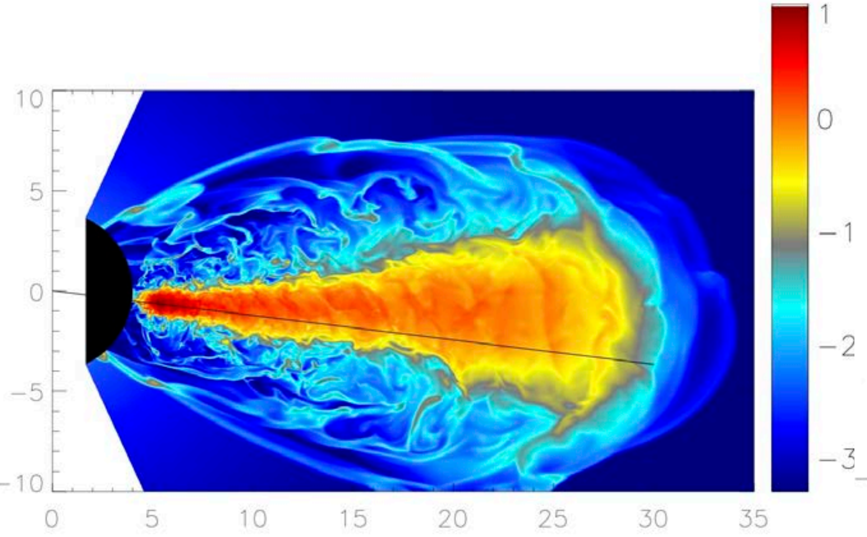
Isothermal Keplerian Disk
H/r ~ 0.035

(765x765x1024)

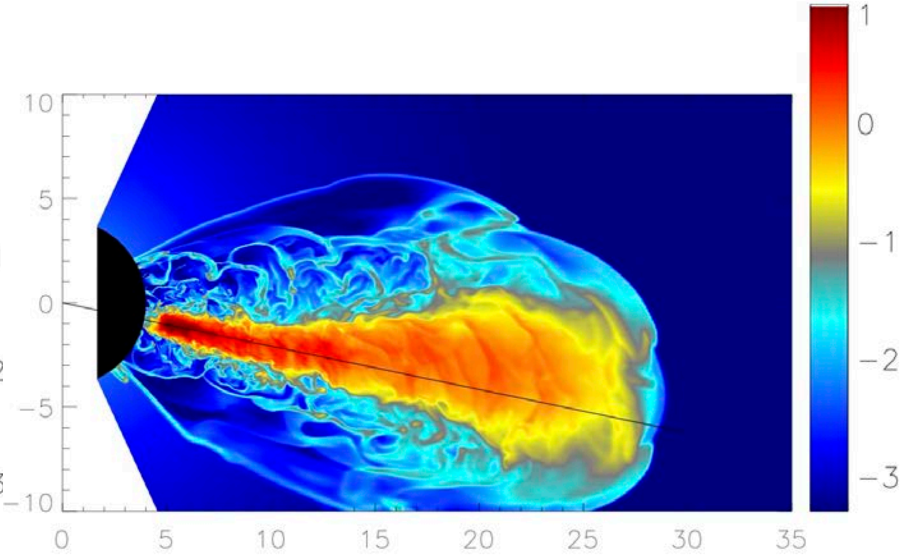
Location of 75% alignment as a function of sound speed



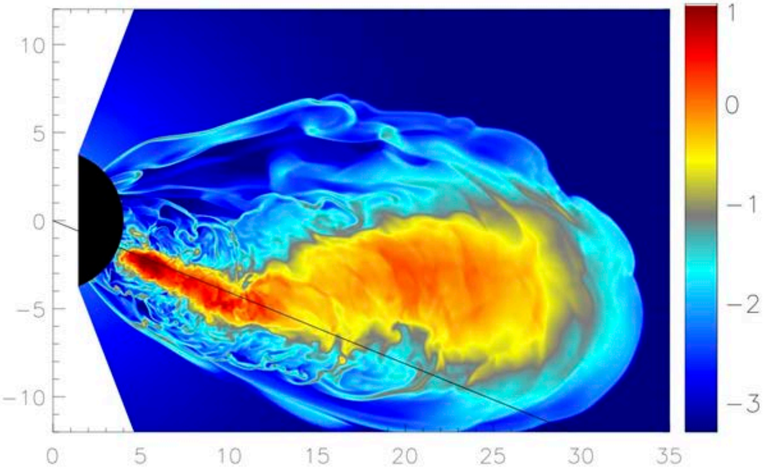
Comparison of three tilt angles



Tilt = 6 degrees



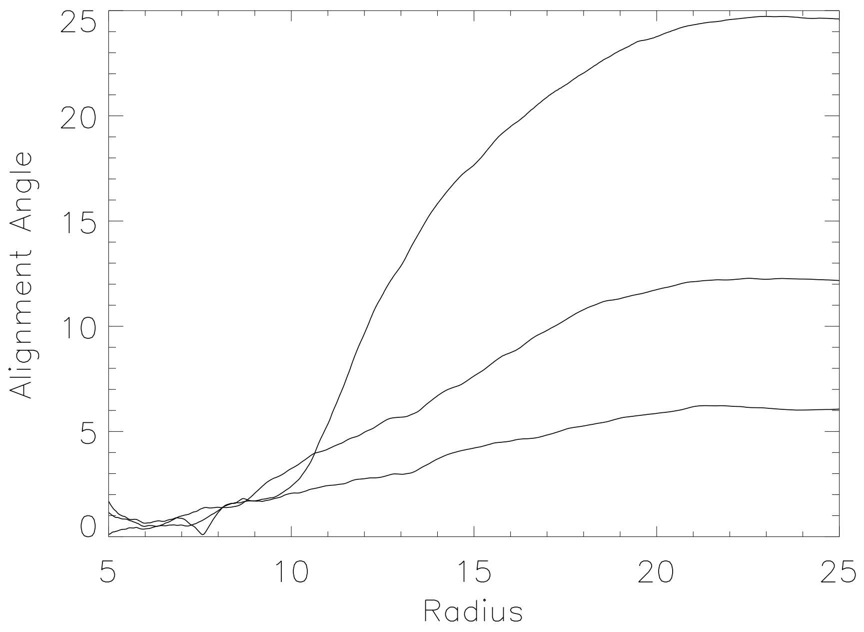
Tilt = 12 degrees



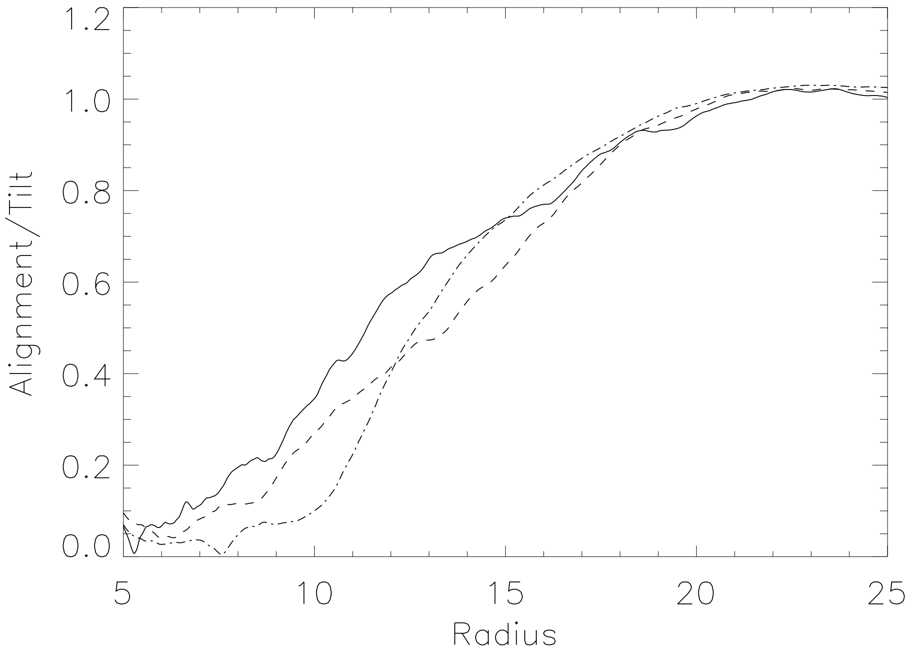
Tilt = 24 degrees

No evidence for ”disk breaking” for these three tilts

Alignment angle: three tilts



Absolute value of alignment angle



Ratio of Alignment to tilt

Results Summary

- Primary dynamical forces are hydrodynamic in nature (bulk Reynolds stresses from radial pressure gradients)
- MHD turbulence does not produce isotropic stress; no significant out-of-plane MHD stress
- The difference between pure hydro and MHD is that the latter is turbulent. MHD turbulence disrupts internal wave motion and inhibits evolution toward solid-body precession
- Transition front determined by balance between external torque and warp induced inward mixing of angular momentum
- Diffusion model predicts alignment radius $R_T \sim c_s^{-4/5}$ – results consistent with this
- Warp amplitude is the relevant physical discriminant for characterization as wavelike or diffusive
- Alignment process depends only weakly on tilt angle (up to 24 degrees)