Stability In Dilute Magnetized Accretion Plasmas

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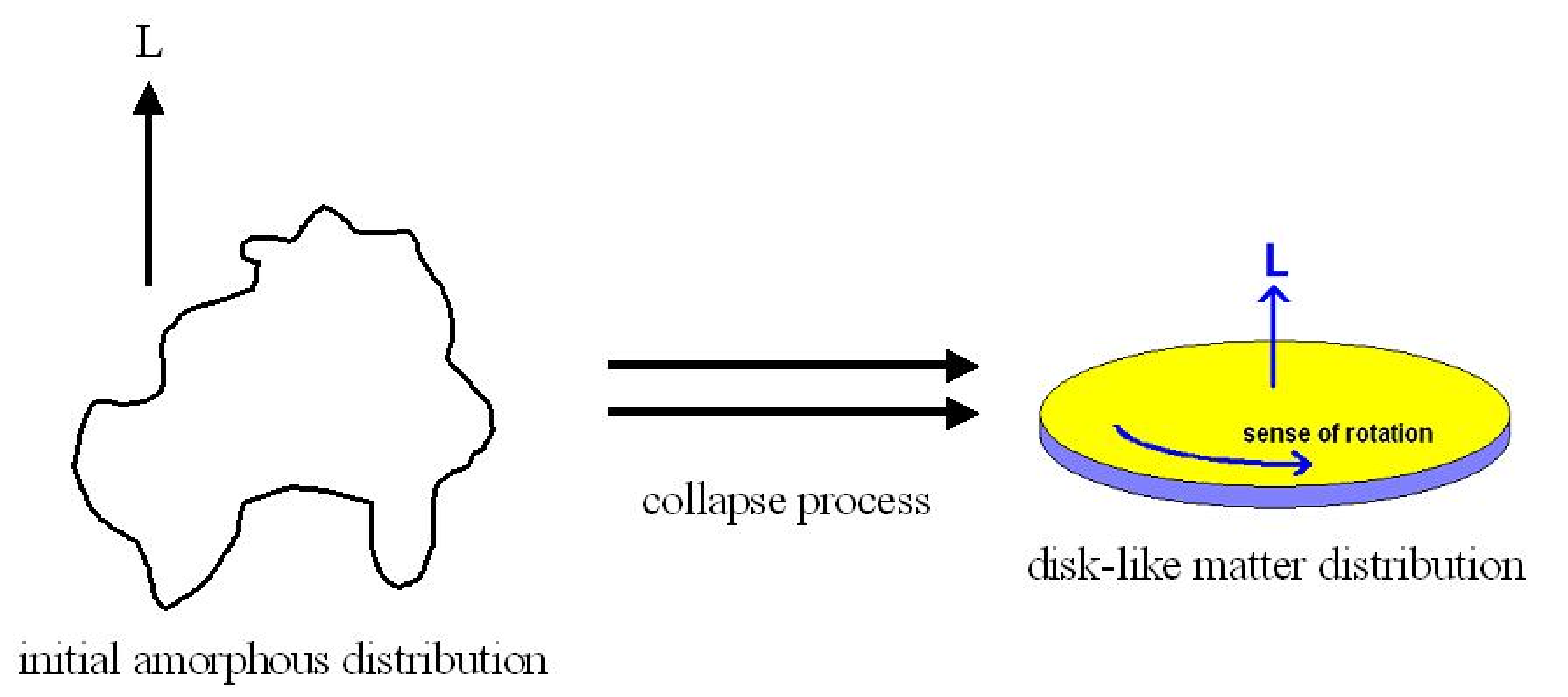
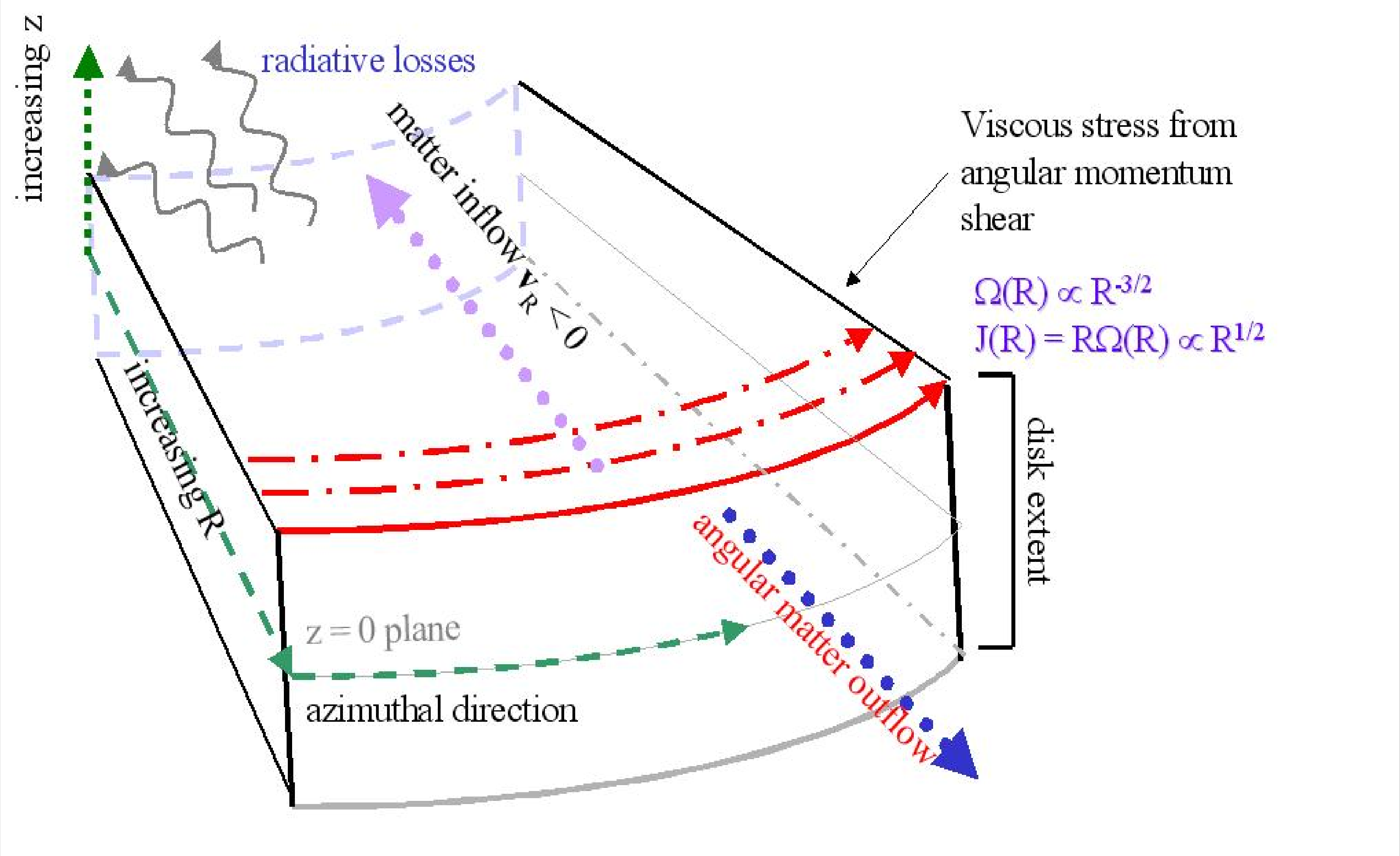
Disks are natural objects in astrophysics

- much easier to get rid of energy than angular momentum.



The typical method to explain accretion is a viscosity due to differential rotation between disks:

- transfer of angular momentum **outwards**
- transfer of matter **inwards**



Diffusion Equation For Accretion

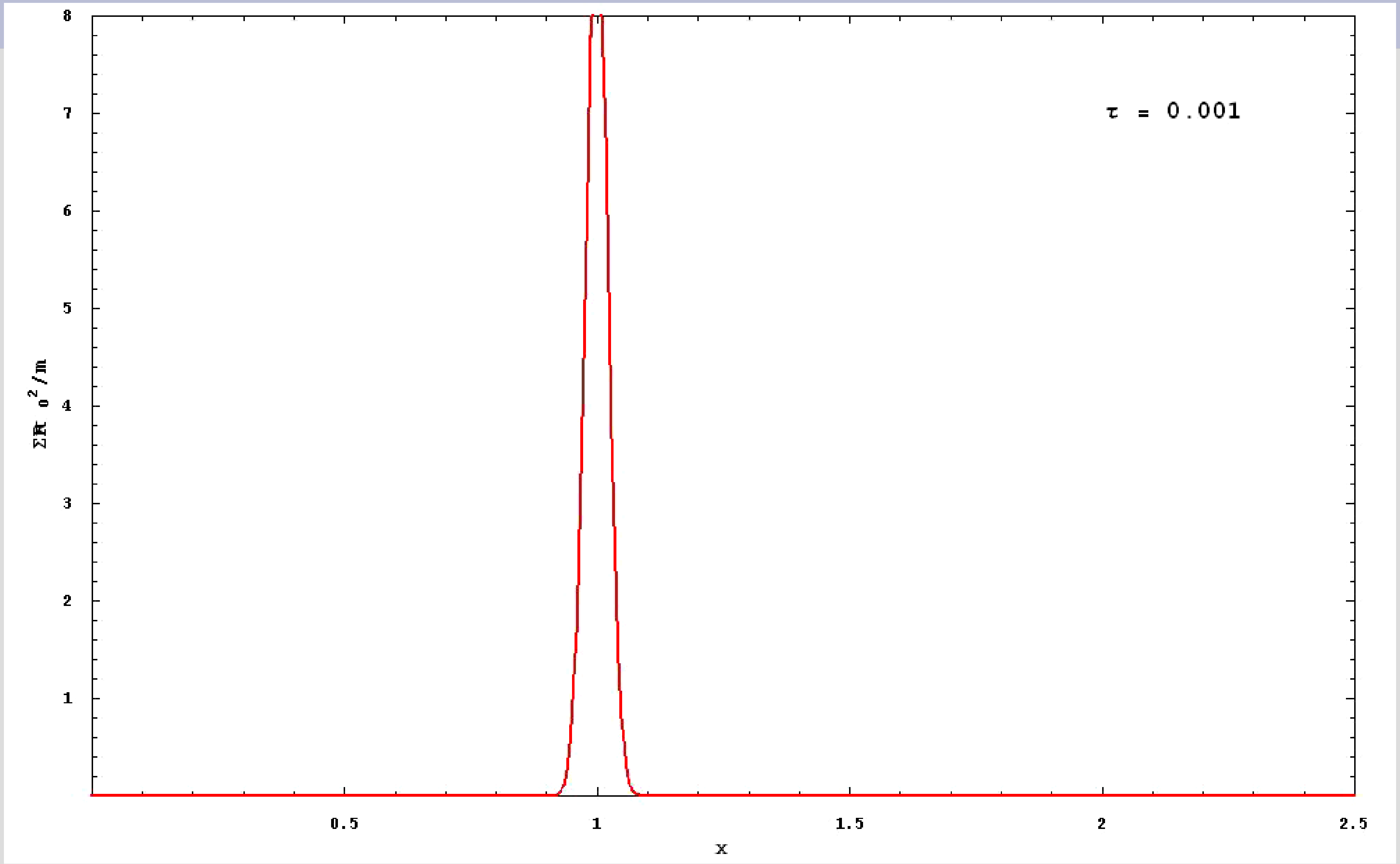
$$v(R,t)=\frac{1}{R\Sigma\, d(R^2\Omega)/dR}\frac{d}{dR}(\eta_\nu \Sigma R^3 \frac{d\Omega}{dR})$$

$$\frac{d\Sigma}{dt}=-\frac{1}{R}\frac{d}{dR}[\frac{1}{d(R^2\Omega)/dR}\frac{d}{dR}(\eta_\nu \Sigma R^3 d\frac{\Omega}{dR})]$$

- $\eta_\nu = \alpha_{SS}$ $\mathbf{c_s H}$ is the Shakura-Sunyaev[1] viscosity (equivalently, with viscous stress $T_{R\phi} = \alpha_{SS}P$), a useful paradigm in characterizing turbulent viscosity in accreting flows -- the size of the cells is **H** (disk thickness); the sound crossing speed is $\mathbf{c_s}$ (sound speed)

[1]A&A **24**, 337 (1973).

ANIMATION OF THE VISCOUS TRANSPORT OF MATTER AND ANGULAR MOMENTUM IN AN ACCRETION DISK

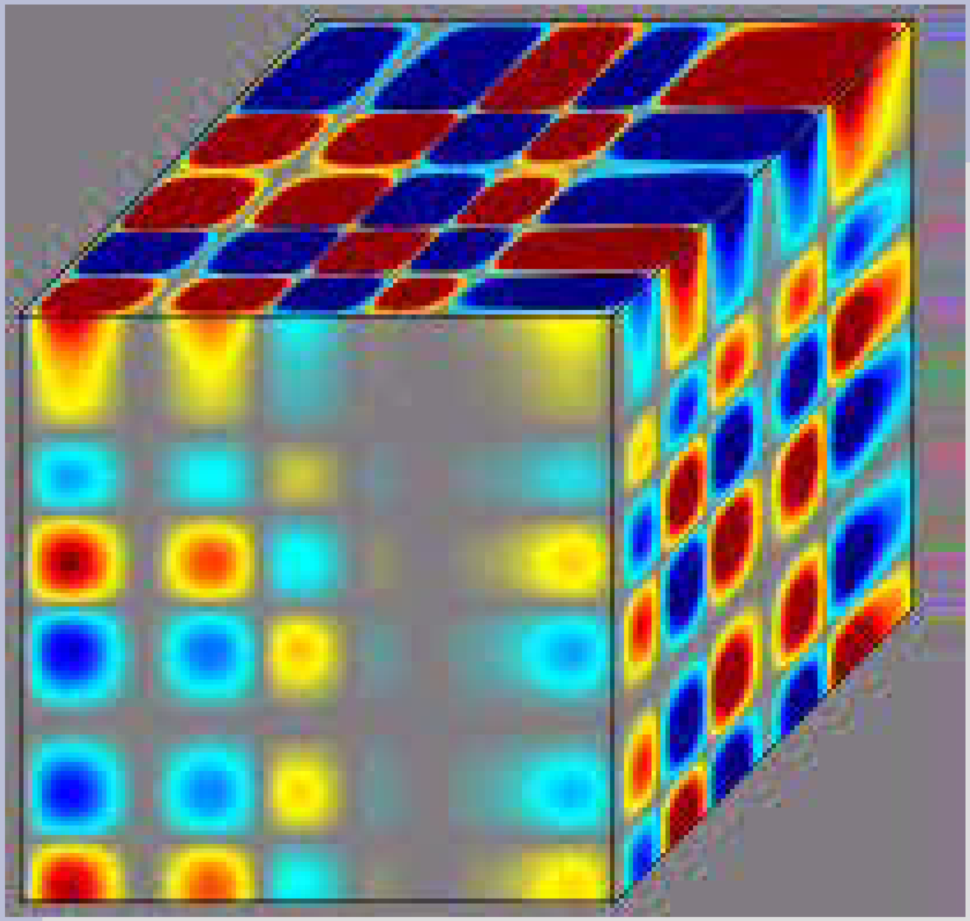


The Magnetorotational Instability

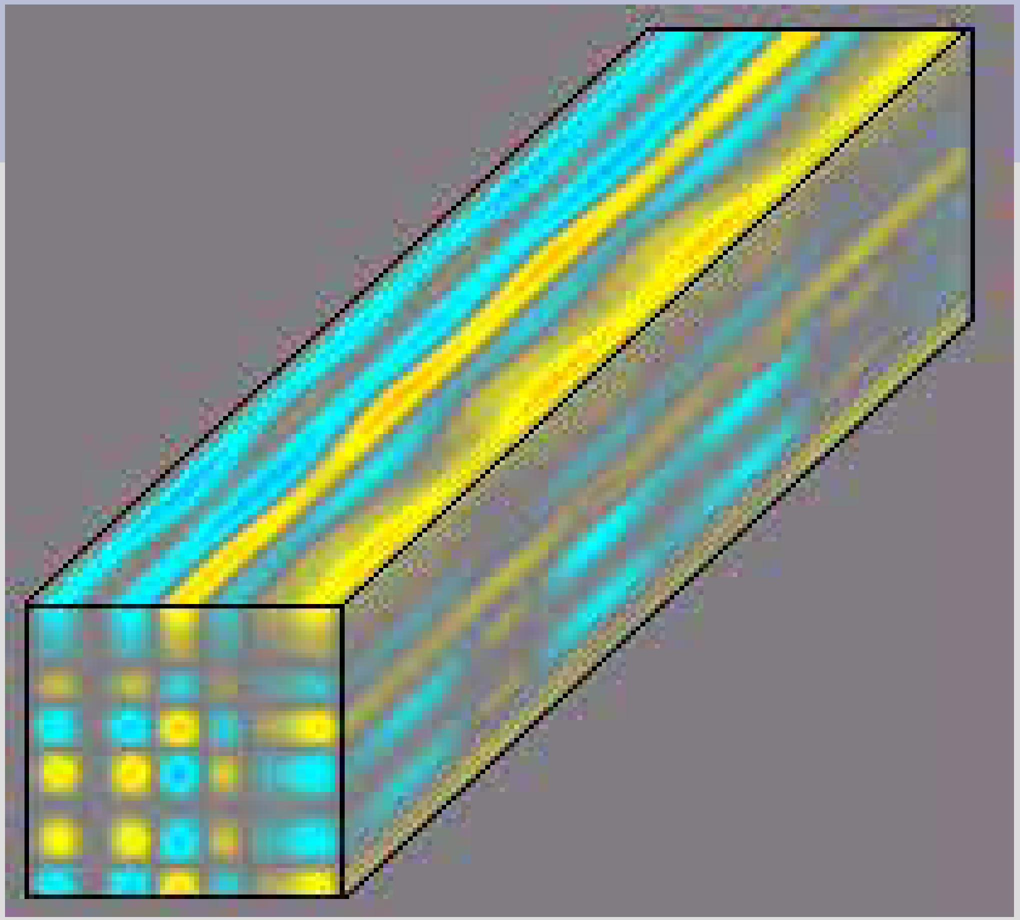
- First discovered by Velikhov[1] and Chandrasekhar[2], and applied to the problem of disk accretion by Balbus & Hawley[3].
- Systems in which the **angular velocity** Ω rather than angular momentum ΩR^2 (in hydrodynamic flows) are unstable to these modes.
- Instability grows at the rate of Ω at wavelengths much **smaller** than the disk height ("turbulence" within the disk arising from magnetic fields).

[1]Sov. Phys. JETP **36**, 995 (1959).
[2]Proc. Nat. Acad. Sci. USA **46**, 53 (1960).
[3]ApJ **376**, 214 (1991).

Demonstration of MRI



no magnetic fields



with magnetic fields

Taken from http://www.astro.virginia.edu/VITA/accdisk.html

Stability Discriminants for Magnetized Accretion Disks

	nonmagnetized	magnetized, collisional	magnetized, dilute
angular momentum transport	angular momentum ($\Omega^2 R$) decreases radially outward	angular velocity (Ω) decreases radially outward	angular velocity (Ω) decreases radially outward
energy transfer	entropy ($\log P\rho^{-5/3}$) decreases radially outwards.	entropy ($\log P\rho^{-5/3}$) decreases radially outwards.	temperature decreases radially outwards.

Dilute Plasma MHD Instabilities

- **Magnetoviscous**: analogue to magnetorotational instability in the limit of large ion viscosity.
  - characterized by growth rate saturation at long wavelengths relative to the MRI ($k << \Omega/v_A$).
  - fluid elements tethered due to large viscosity along magnetic field lines.
- **Magnetothermal**:
  - driven by temperature gradients along magnetic field lines.
  - alters the dynamics of the system when disks are fat.
- **Magnetoviscous-thermal**: large anisotropic magnetized thermal conductivity and viscosity

Astrophysical Applications: NRAFs

- very hot ($k_B T_i \sim m_i c^2$) and steady flows around black holes
  - nonradiative: dynamically insignificant fraction of energy is radiated (by electrons) as matter accretes onto central object.
  - ions are somewhat to significantly hotter than electrons, and adiabatic.
  - accretion rates on the order of Eddington mass accretion rate.
  - **fat disks** – disk height ~ disk radius R.
  - dilute plasmas: dynamically significant thermal conductivities and viscosities.

Main Analytic Models of NRAFs

- **ADAF** (Advection Dominated Accretion Flows) – extension of the thin-disk accretion model out to the regime of very hot optically thin plasmas.
- **CDAF** (Convection Dominated Accretion Flows) – convectively unstable flows with entropy increasing outwards, with convective eddies transporting angular momentum.
- **ADIOS** (Advection-dominated inflow-outflow solutions) – most of disk matter escapes in wind, only small fraction accretes onto black hole. Analytically – accretion rate decrease with radius.

Energy Transport Cannot be Ignored in NRAFs

- From Balbus[1], the equation for energy balance to quadratic order in fluctuations:

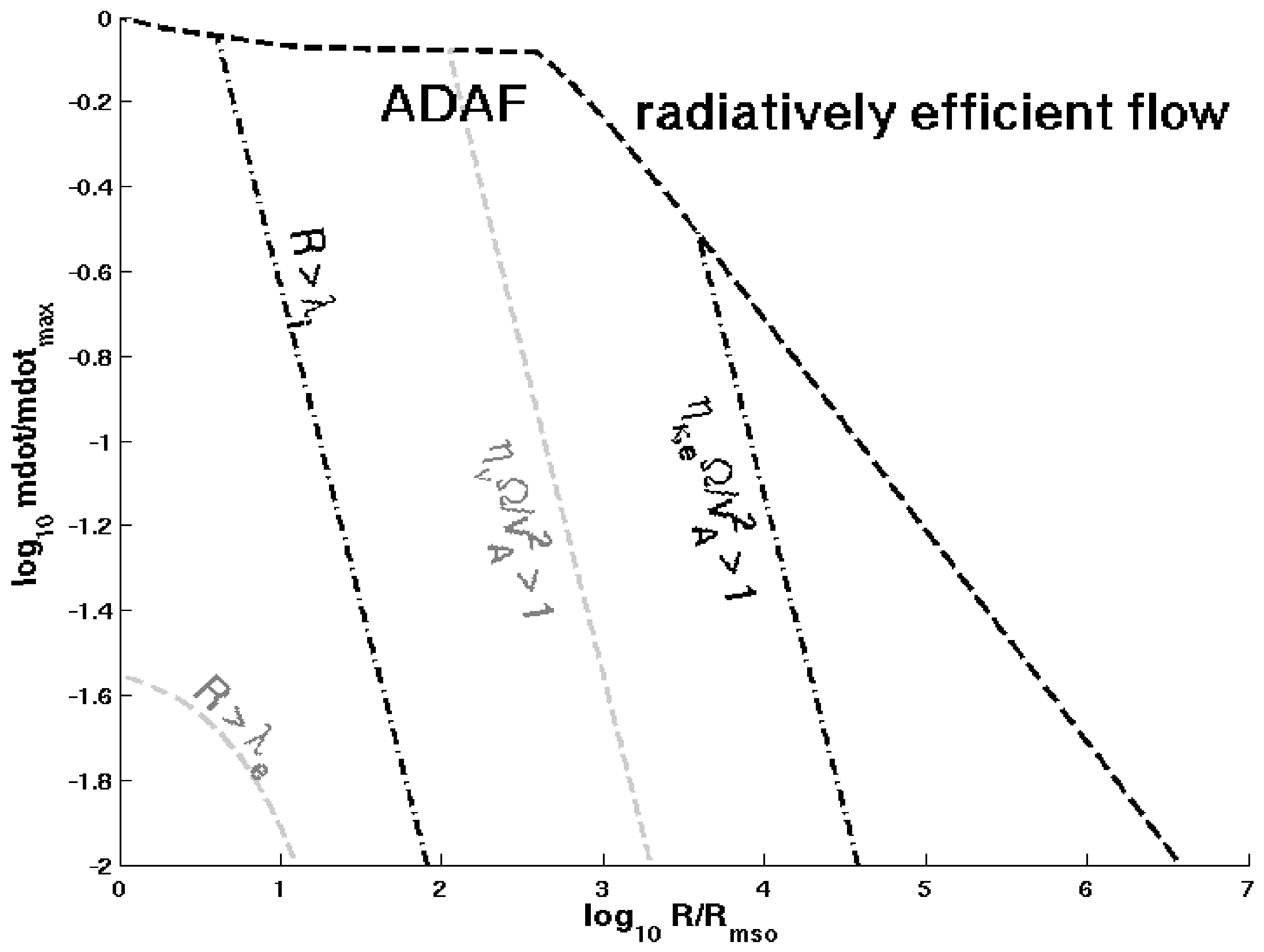
$$\frac{5k_B\rho}{2m_i}\nabla.\langle\delta v_R\delta T\rangle+\frac{3k_B T}{2m_i}\langle\delta\rho\delta v_R\rangle\frac{\partial}{\partial R}\ln P\rho^{-5/3}=\cancel{-Q}-T_{R\phi}\frac{d\Omega}{d\ln R}$$

Heat generated through viscosity must be balanced by at least a heat flux.

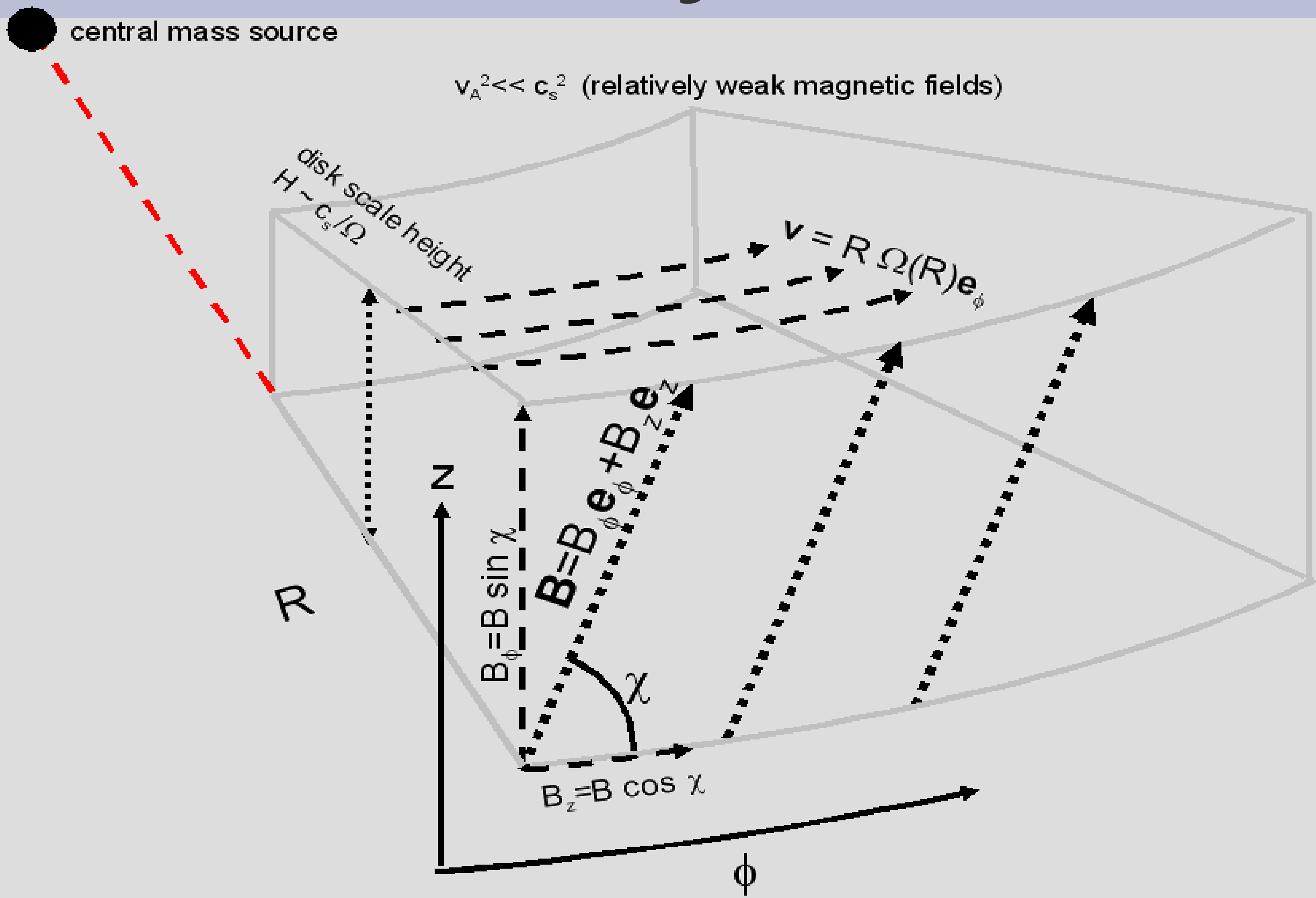
$$\frac{5k_B\rho}{2m_i}\nabla.\langle\delta v_R\delta T\rangle+\frac{3k_B T}{2m_i}\langle\delta\rho\delta v_R\rangle\frac{\partial}{\partial R}\ln P\rho^{-5/3}=-Q-T_{R\phi}\frac{d\Omega}{d\ln R}$$

[1]ApJ **600**, 865 (2004).

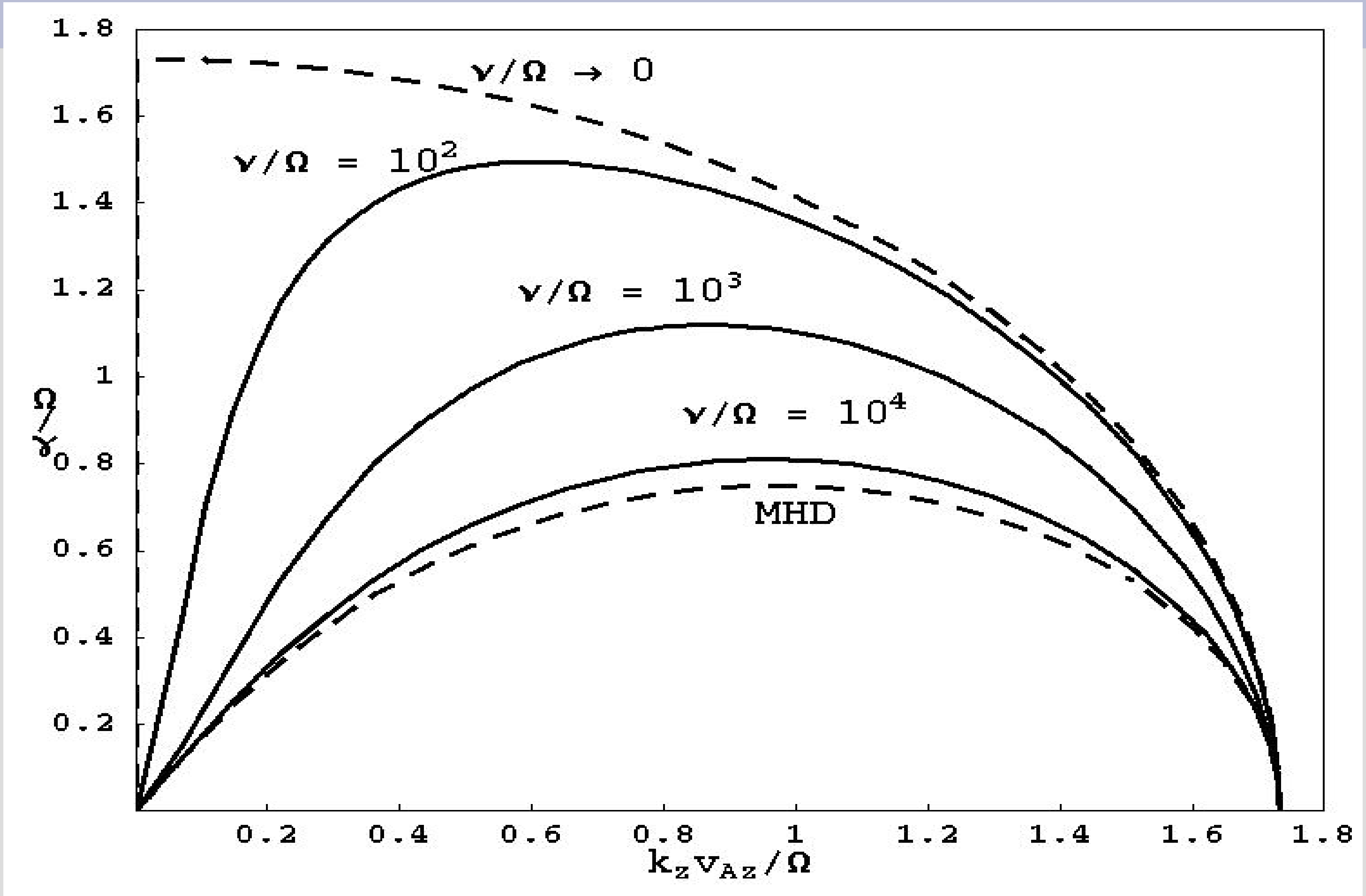
Regime of Applicability of Instabilities



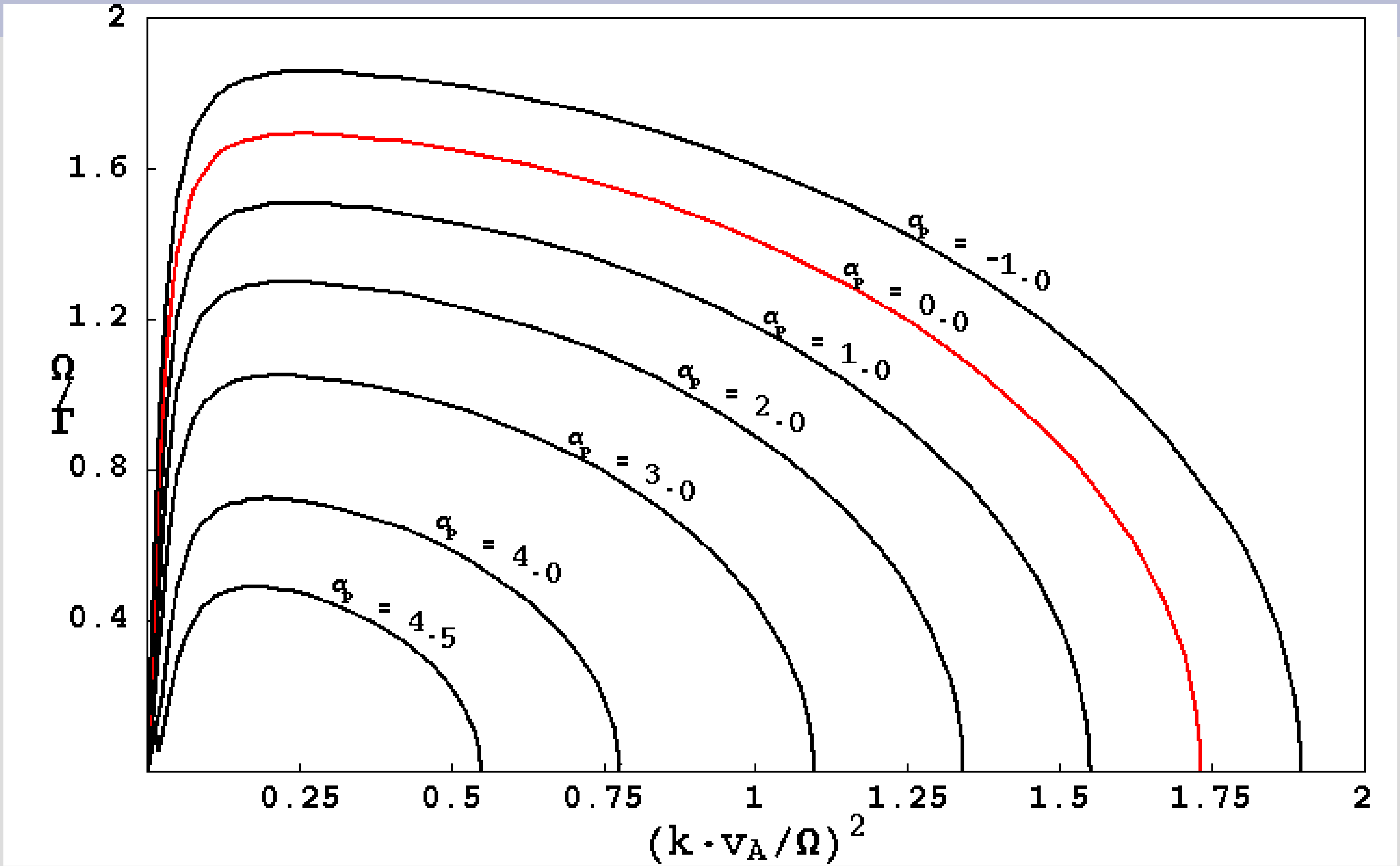
Disk Model Used in Stability Analysis



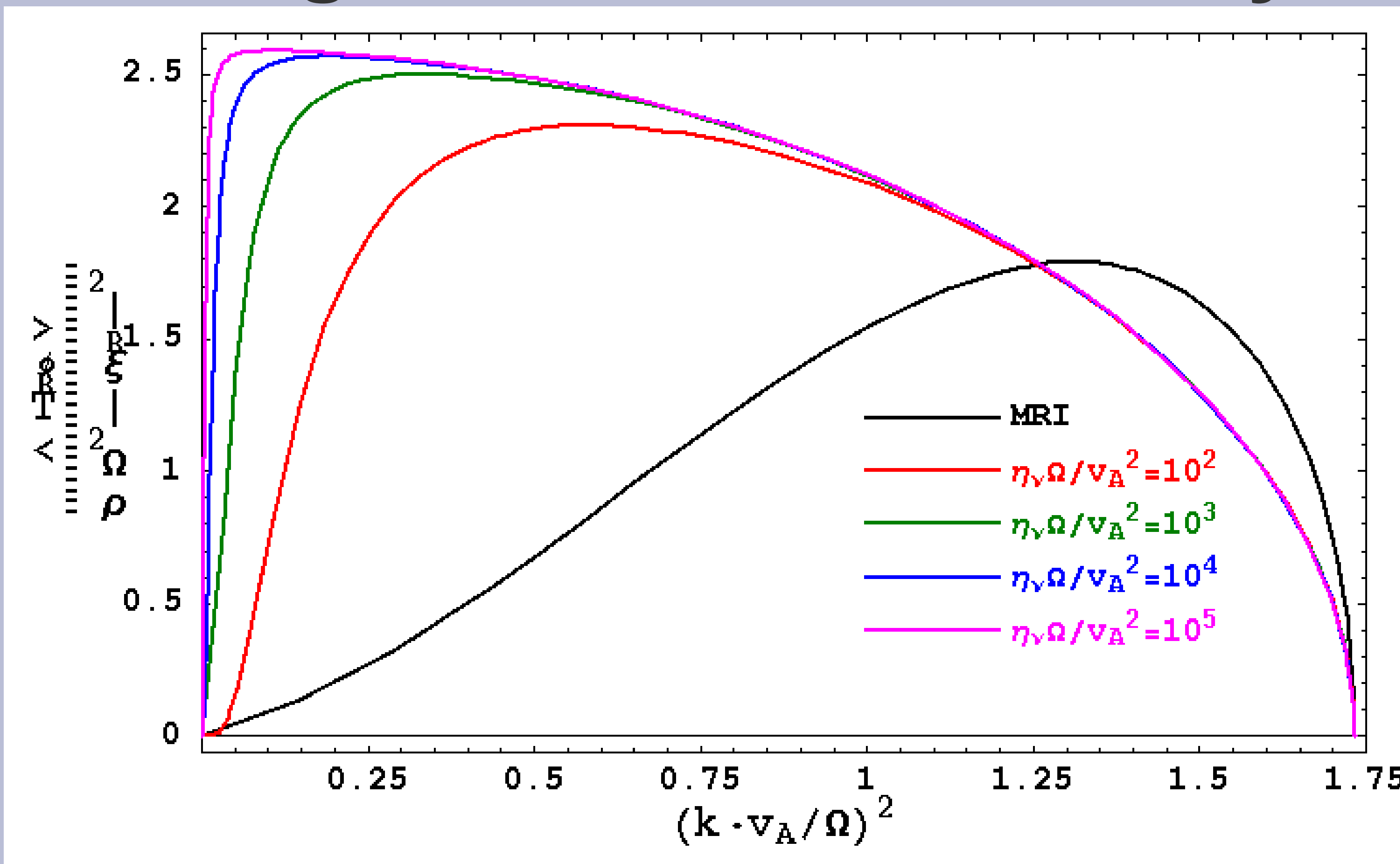
Magnetoviscous Dispersion Relation



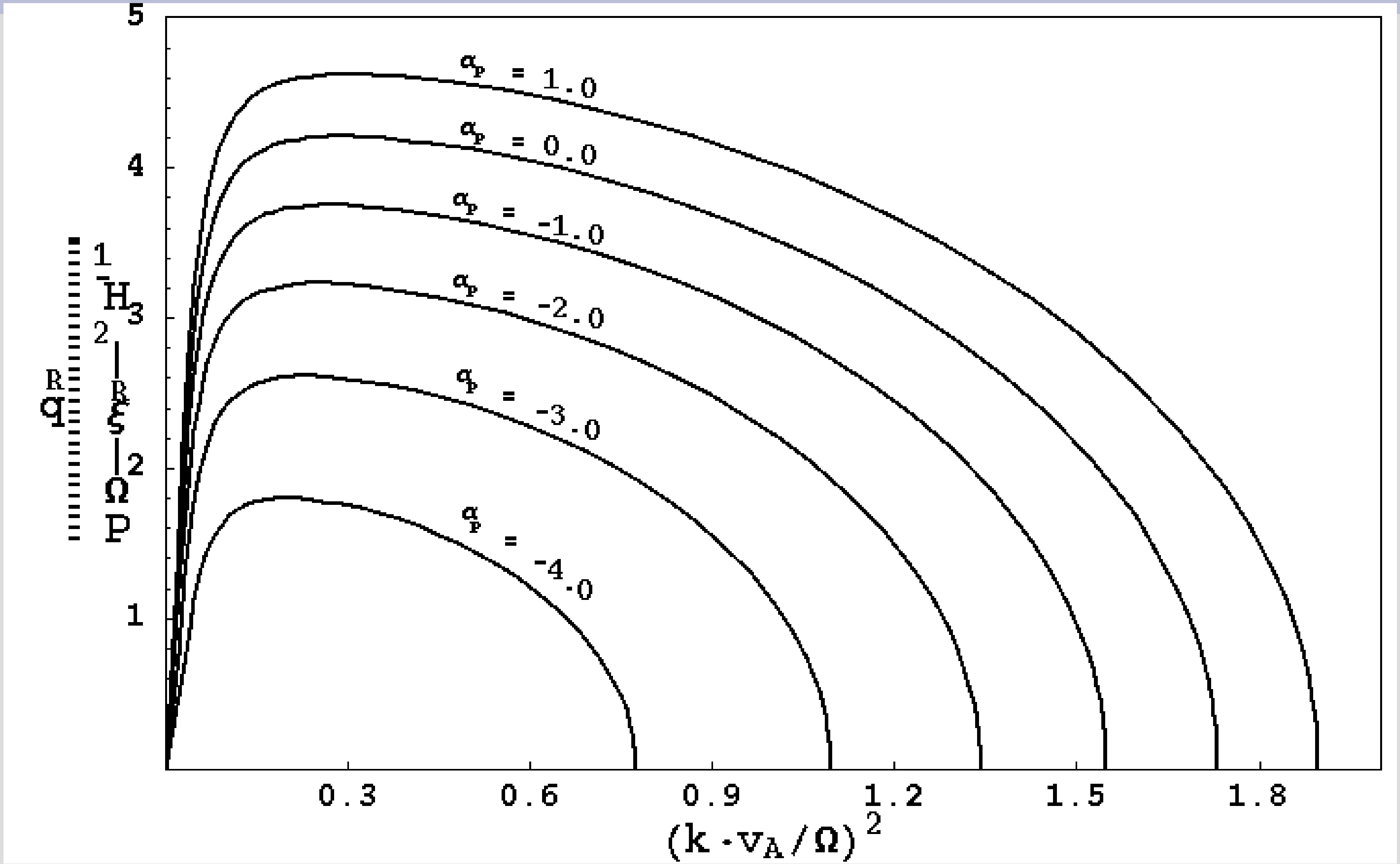
Magnetothermal Dispersion Relation

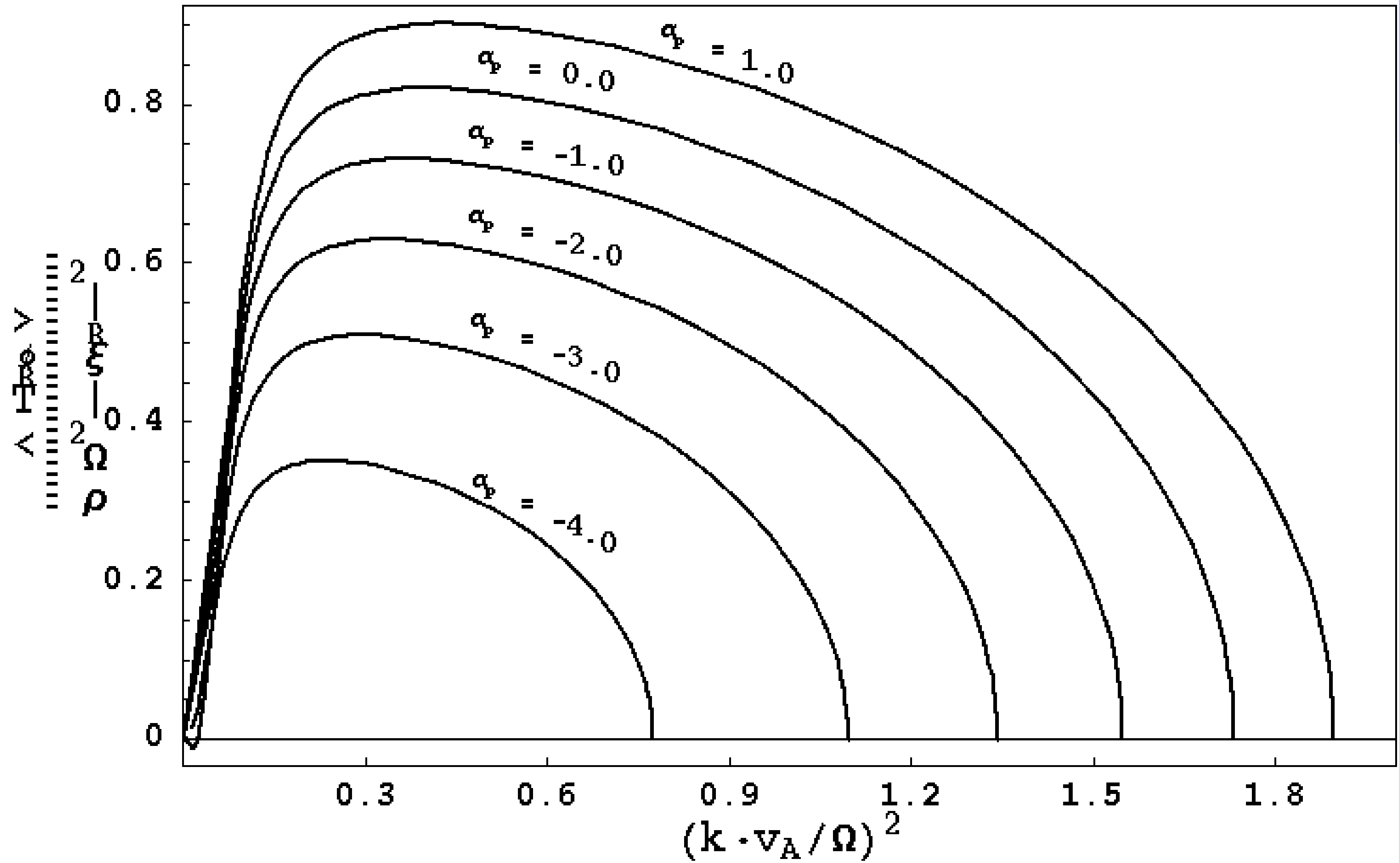


Angular momentum flux of magnetoviscous instability



Outward transport of energy and angular momentum

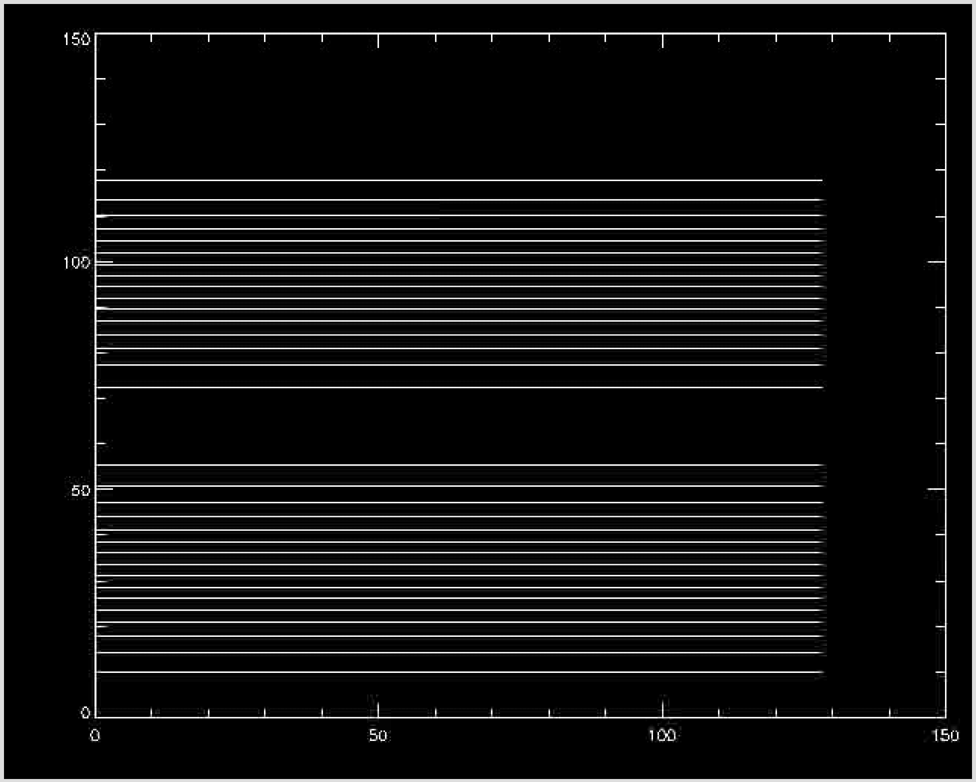



α_p = 1.0
α_p = 0.0
α_p = -1.0
α_p = -2.0
α_p = -3.0
α_p = -4.0
0.8
0.6
0.4
0.2
0
0.3
0.6
0.9
1.2
1.5
1.8
$(k \cdot v_A/\Omega)^2$

Further Research

- Heat fluxes associated with the nonlinear magnetoviscous-thermal instability, by first examining radial slices, in 2D and 3D.
- Global simulation of a flow with these effects included:
  - what is the flow structure? Does the structure settle into a thin (such as in MRI simulations) or fat disk?
  - what is the temperature profile? Of ions and electrons?
- For both local and global simulations, design diagnostic tests for ATHENA code.

Nonlinear Thermal Instability In Magnetized Plasma



magnetic field lines

temperature

Taken from http://www.astro.princeton.edu/~iparrish