The Magnetothermal Instability (MTI) And Its Role in Hot, Dilute Magnetized Accretion

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Overview of Talk

- The magnetothermal instability – what is it?
- Astrophysical justification for this line of research.
- Stability analysis showing that new MHD instabilities can drive accretion.
- Further numerical research.

The MTI and MVI

- In highly collisional astrophysical MHD plasmas, the magnetorotational instability (MRI) acts to transport angular momentum and allows for accretion to occur; Balbus and Hawley (1991) noted its promising role in allowing for astrophysically measurable accretion.
- In dilute plasmas, even with dynamically unimportant magnetic forces, in which ion cyclotron frequency $\gg$ inverse time scales of our problem of interest (such as collision frequency), momentum and energy transport become anisotropic and dynamically important:
  - The magnetothermal instability (MTI) transports thermal energy via magnetic-field-directed thermal flux where temperature decreases upwards/outwards (Balbus, 2001).
  - The magnetoviscous instability (MVI) transports angular momentum outwards, via magnetic-field directed viscous stresses, when angular velocity decreases outwards (Balbus, 2004; Islam and Balbus, 2005).
  - MHD wave-plasma interactions result in similar levels of viscous and thermal transport in the collisionless limit (see Quataert et al. (2002); Sharma et al. (2003)).

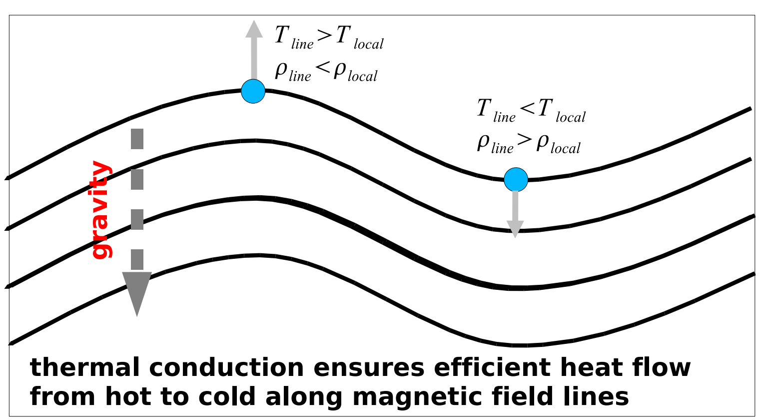
Physical Models of the MVI and MTI

Heat flux and viscosity:

heat flux: $\mathbf{q} = q\mathbf{b}$

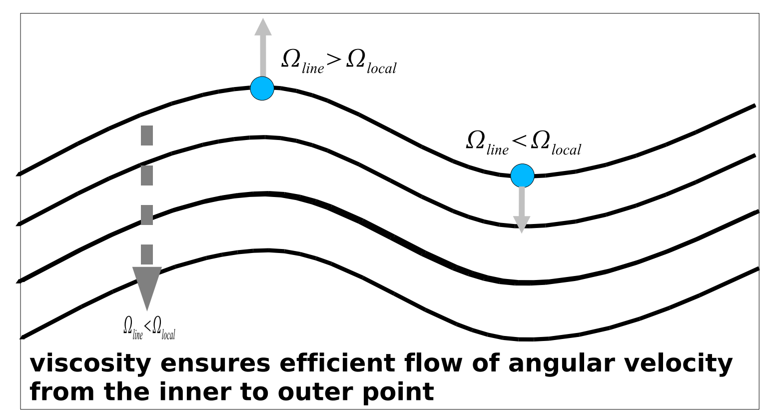
viscous stress tensor: $\boldsymbol{\sigma} = \sigma_{\mathbf{bb}} \left(\mathbf{bb} - \frac{1}{3}\mathbb{I} \right)$

COLD



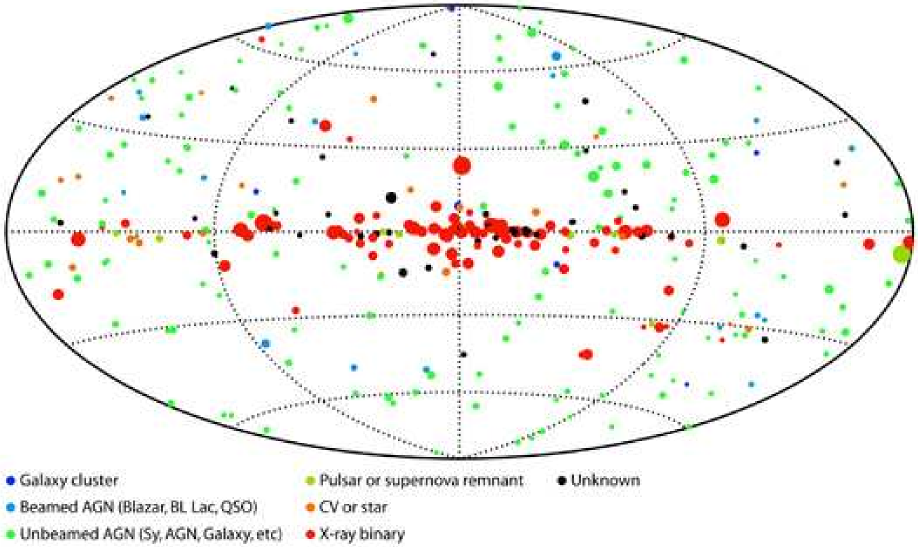
HOT

MTI



MVI

Rarity of High-mass rate accretors in the centers of galaxies

- 

  Only $\sim$ 400 AGNs (high-mass-rate accretion black holes) lie within 4×10^8 ly (Winter et al., 2007).

- Strong evidence of orders of magnitude more central galactic SMBHs than AGNs and quasars in the current epoch (Richstone et al., 1998).

Best Example: Underluminosity of Sag. A*

- Baganoff et al. (2003) measures $n_e \sim 10^2$ cm^{-3} and $T_e \sim 2$ keV at $1''$ from Sag. A. Sag. A, located 8.5 kpc away. This implies:
  - $R_{\text{c}} \simeq 2.9 \times 10^{17}$ cm $\equiv 2.4''$ from Sag. A.
  - $\dot{M}_B \sim 5.6 \times 10^{-6}\ M_\odot$ yr^{-1}.
  - $L_{\text{Bondi}} \sim 3.2 \times 10^{40}$ erg s^{-1}, assuming 10% mass-energy efficiency for black hole accretion.
- However, bolometric luminosity of Sag. A: $L \sim 10^{36}$ erg s^{-1} $\sim 3 \times 10^{-5} L_{\text{Bondi}}$!

Dilute nature of underluminous accretion

This figure is borrowed from Menou (2005) n is in units of cm^{-3}; T in units of 10^7 K; and R in cm. Inner regions (near BHs) are highly collisionless.

Galaxy	$n\,(1")$	$T\,(1")$	$R\,(1")$	$\lambda\,(1")\,/R\,(1")$	$\lambda\,(1")\,/R_{\text{Bondi}}$
Sag. A*[a]	100	2.3	1.3×10^{17}	0.4	0.4
NGC 1399[b]	0.3	0.9	3.1×10^{20}	0.009	0.02
NGC 4472[b]	0.2	0.9	2.5×10^{20}	0.016	0.07
NGC 4636[b]	0.07	0.7	2.2×10^{20}	0.032	0.6
M 82[c]	0.17	0.9	2.7×10^{20}	0.018	0.02
M 32[d]	0.07	0.4	1.2×10^{19}	0.2	1.3

[a] Taken from Baganoff et al. (2003)

[b] Taken from Baganoff et al. (2003)

[c] Taken from Di Matteo et al. (2003)

[d] Taken from Ho et al. (2003)

Mechanics of Dilute Accretion

- Accretion requires angular momentum to be transported outwards, and energy generated from gravitational infall to be transported or dissipated (cannot be radiated):

$$2\pi R^2 \langle T_{R\phi}\rangle + R\Omega(R)\dot{M} = R_{\text{in}}\Omega\left(R_{\text{in}}\right)\dot{M}$$

$$\frac{1}{R}\frac{\partial}{\partial R}R\langle q_R\rangle - \frac{\dot{M}}{2\pi R^2}\left(\frac{1}{\rho_0}\frac{\partial p_0}{\partial R}\right) = -\frac{\partial\Omega}{\partial \ln R}\langle T_{R\phi}\rangle$$

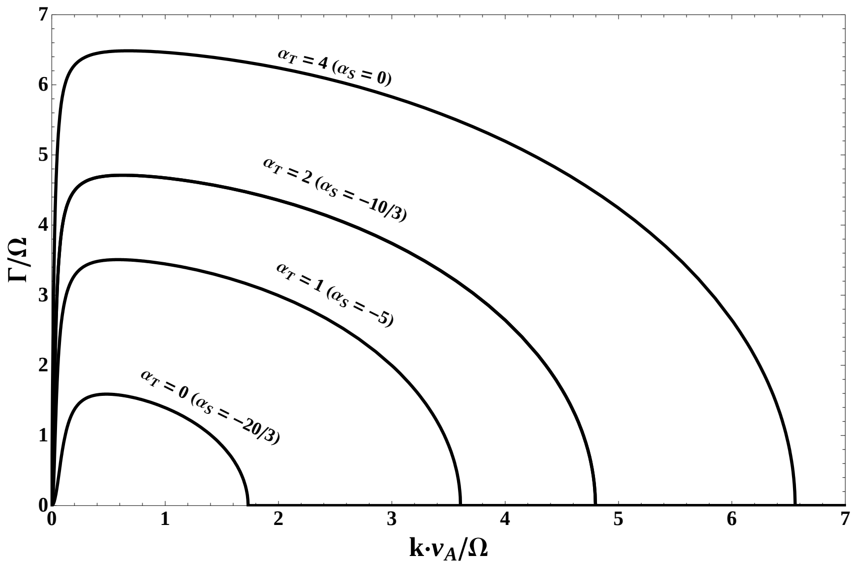
- **Angular momentum flux**: $T_{R\phi} = \left\langle \rho_0 \delta u_R \delta u_\phi - \frac{\delta B_R \delta B_\phi}{4\pi} + \delta\sigma_{\mathbf{bb}}\delta b_R \cos\chi \right\rangle > 0$.

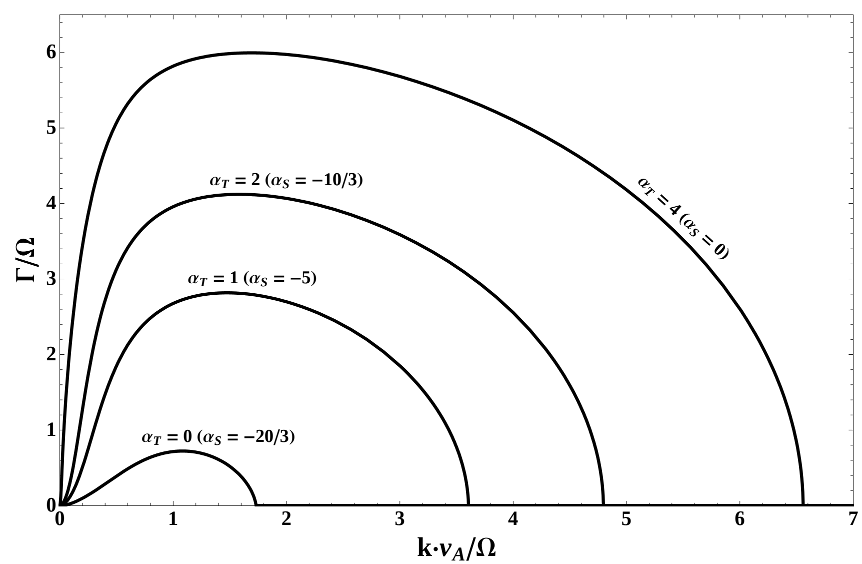
- **Radial heat flux**: $q_R = \left\langle \frac{5}{2}\rho_0 \delta\theta\delta u_R + \delta q \delta b_R - \frac{1}{3}\delta\sigma_{\mathbf{bb}}\delta u_R\right\rangle > 0$. In the MRI, $q_R = 0$.

Stability Analysis

- Axisymmetric nonradial modes, $\delta a \propto \exp\left(ik_Z z + \Gamma t\right)$.
- Equilibrium radial in pressure and temperature such that system is Schwarzchild stable (specific entropy increases outwards).
- Collisional limit: magnetoviscous-thermal instability (MVTI) – both Braginskii viscosity and thermal conductivity.
- Collisionless limit: collisionless MTI.

MVTI Dispersion Relation

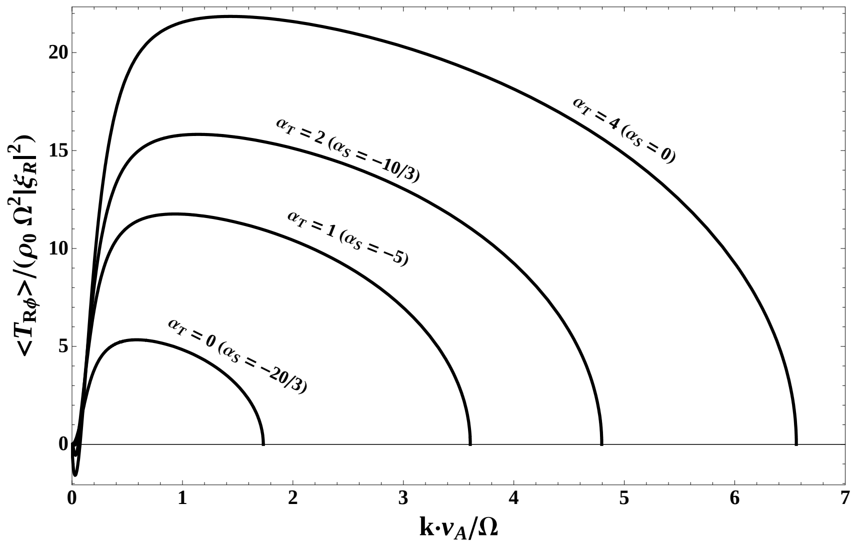




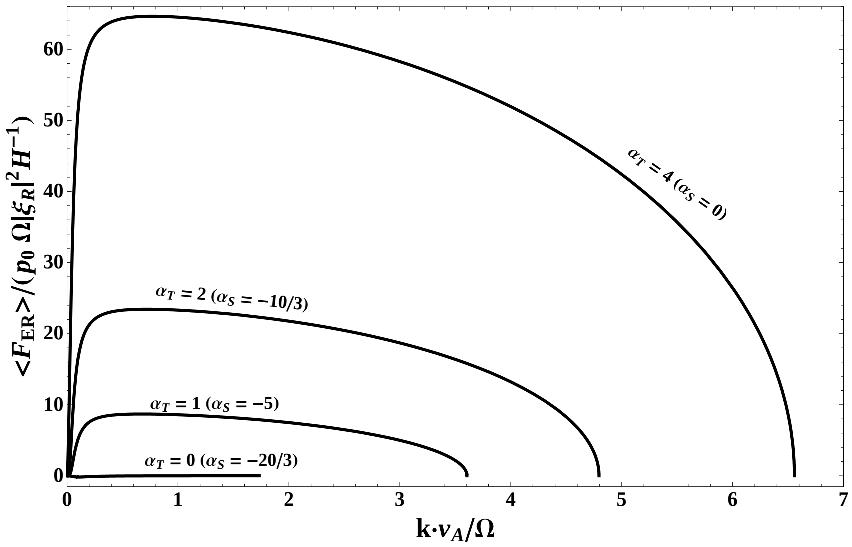
Plot of the MVTI dispersion relation for $\eta_\nu \Omega / v_A^2 = 10^2$.

Plot of the MVTI dispersion relation for $\eta_\nu \Omega / v_A^2 = 1$.

MVTI Quadratic Fluxes



Normalized $\langle T_{R\phi} \rangle$

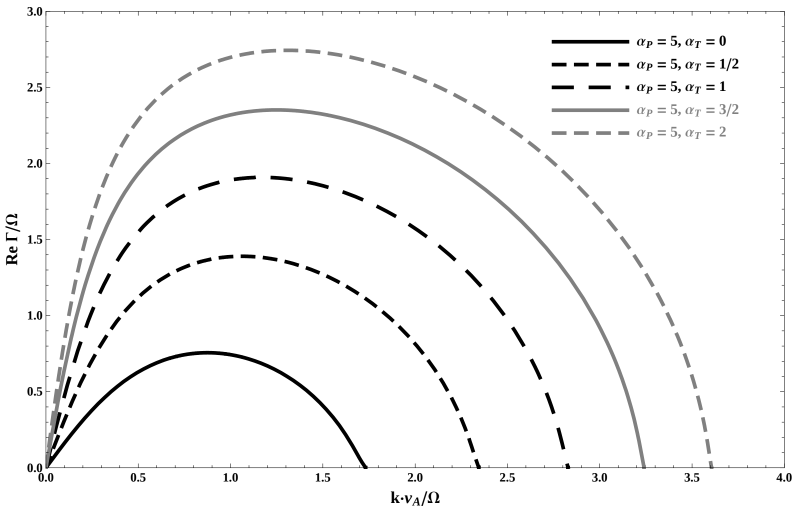


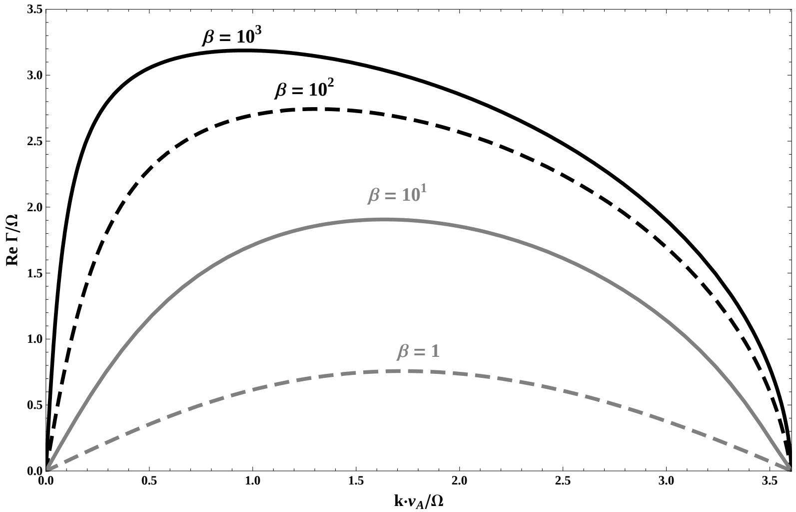
Normalized $\langle q_R \rangle$

Collisionless MTI Dispersion Relation

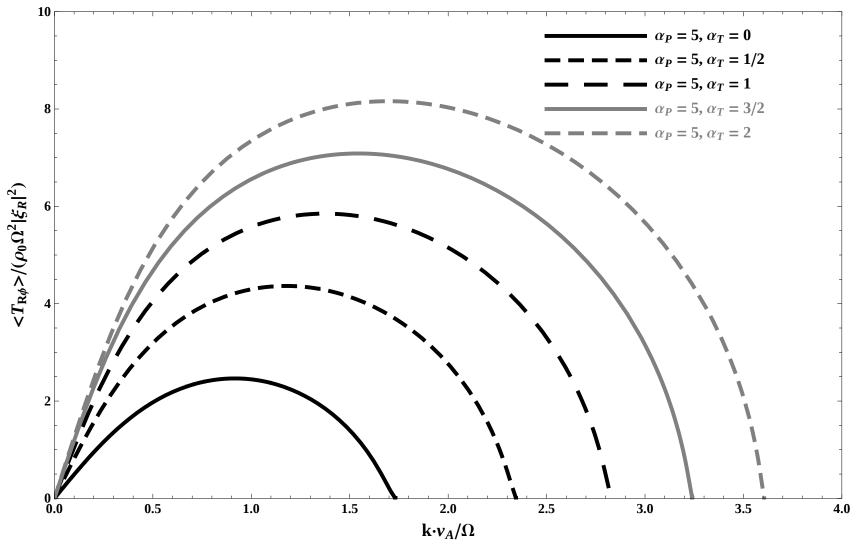
- Collisionless damping of long-wavelength modes with phase velocities of the order sound speed, $k_{\|} \lesssim \Omega \theta_0^{1/2}$.

- As $\beta \to 1$, the collisionless fluxes of momentum and viscosity become dynamically unimportant.

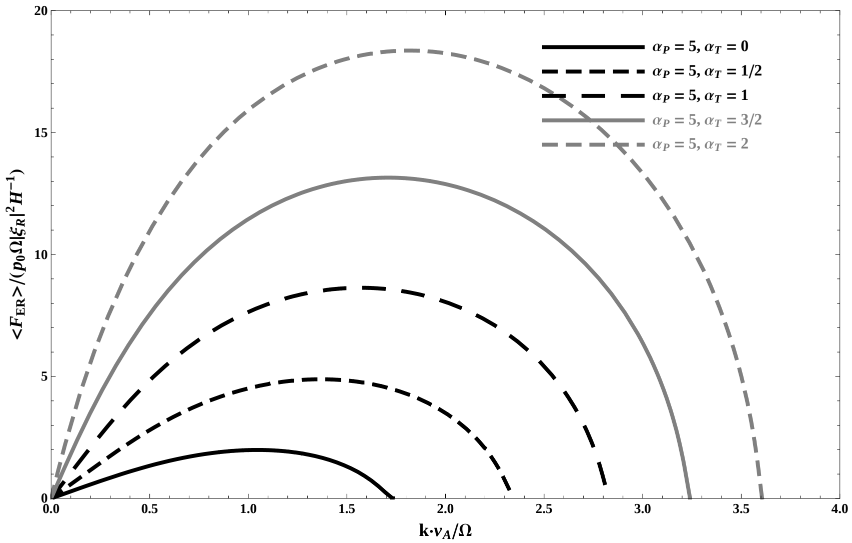




Collisionless MTI Quadratic Fluxes



Normalized $\langle T_{R\phi} \rangle$



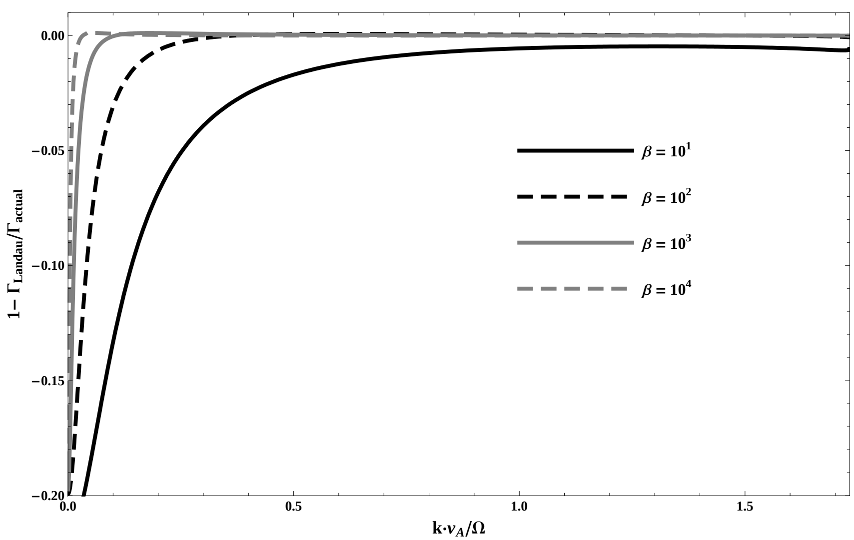
Normalized $\langle q_R \rangle$

Improved Landau Fluid Closures Necessary

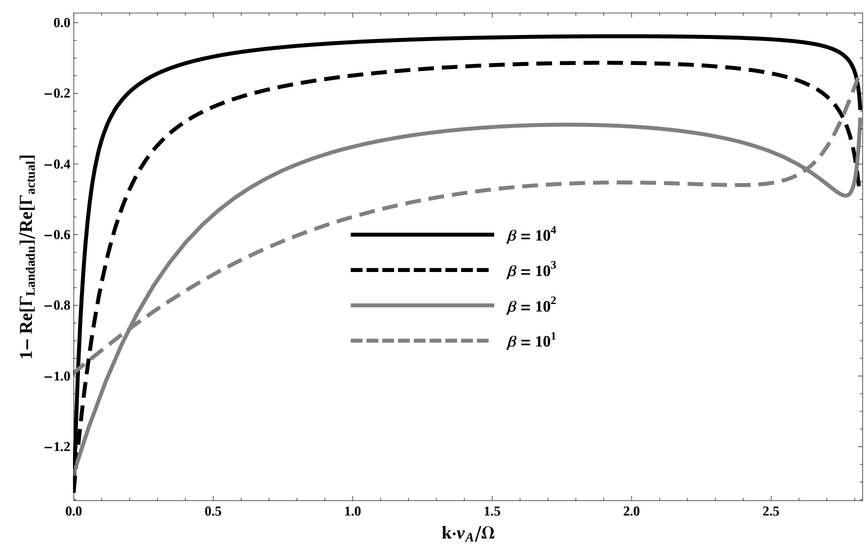
Standard forms of heat fluxes in a collisionless MHD plasma (Snyder et al., 1997):

$$\frac{\delta q_{||}}{p_{i0} v_i} = 2i\sqrt{\frac{2}{\pi}}\left(\frac{\delta\rho}{\rho_0} - \frac{\delta p_{||}}{p_{i0}}\right) - 2\left(\frac{1}{k_{||}}\frac{\partial \ln T_0}{\partial R}\right)\sqrt{\frac{2}{\pi}}\frac{\delta B_R}{B_0}$$

$$\frac{\delta q_{\perp}}{p_{i0} v_i} = i\sqrt{\frac{2}{\pi}}\left(\frac{\delta\rho}{\rho_0} - \frac{\delta p_{\perp}}{p_{i0}}\right) - \left(\frac{1}{k_{||}}\frac{\partial \ln T_0}{\partial R}\right)\sqrt{\frac{2}{\pi}}\frac{\delta B_R}{B_0}$$

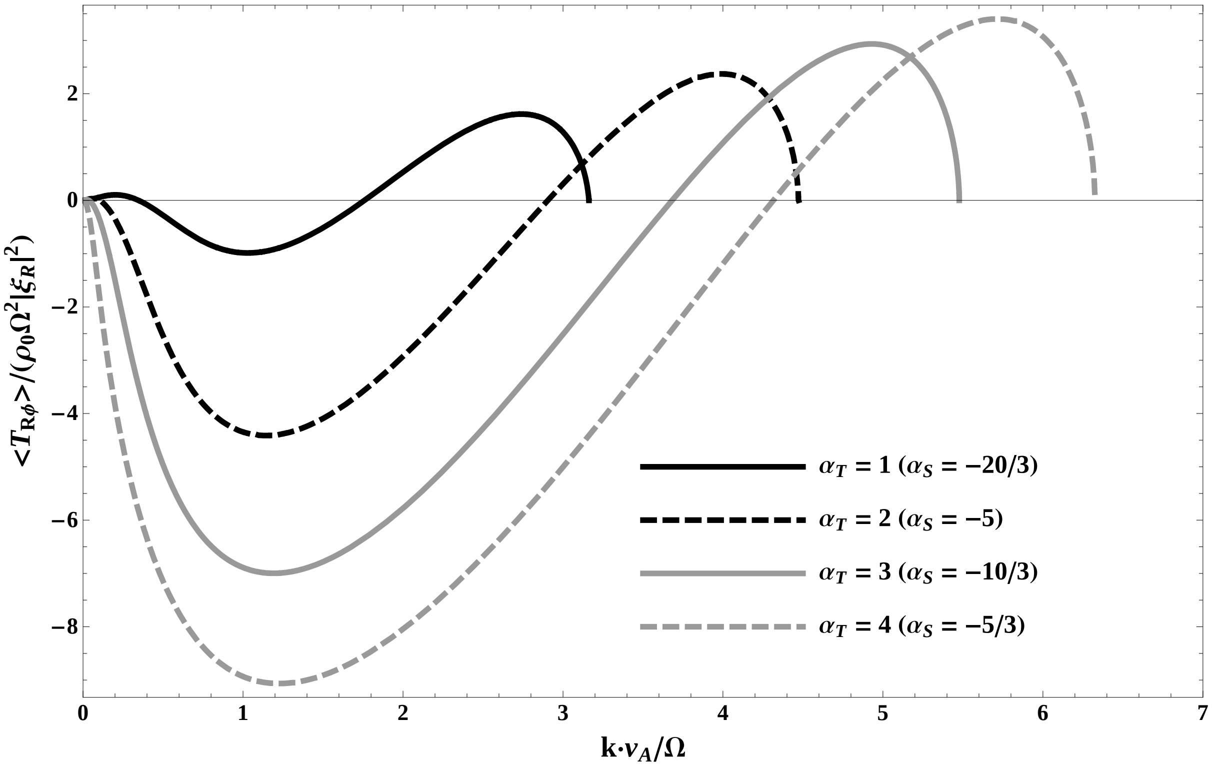


Collisionless MRI



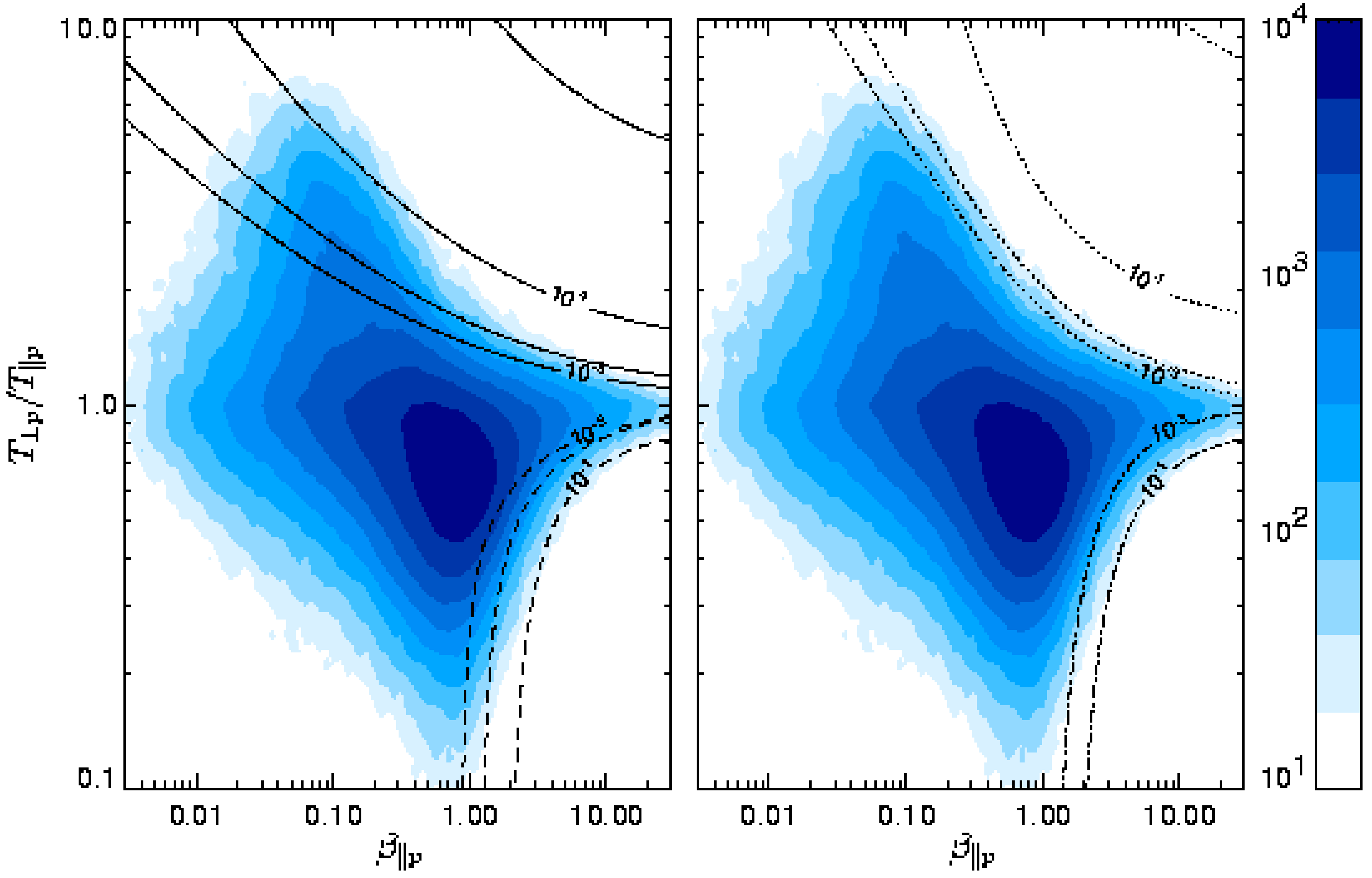
Collisionless MTI

Studies of Angular Momentum Transport in MTI



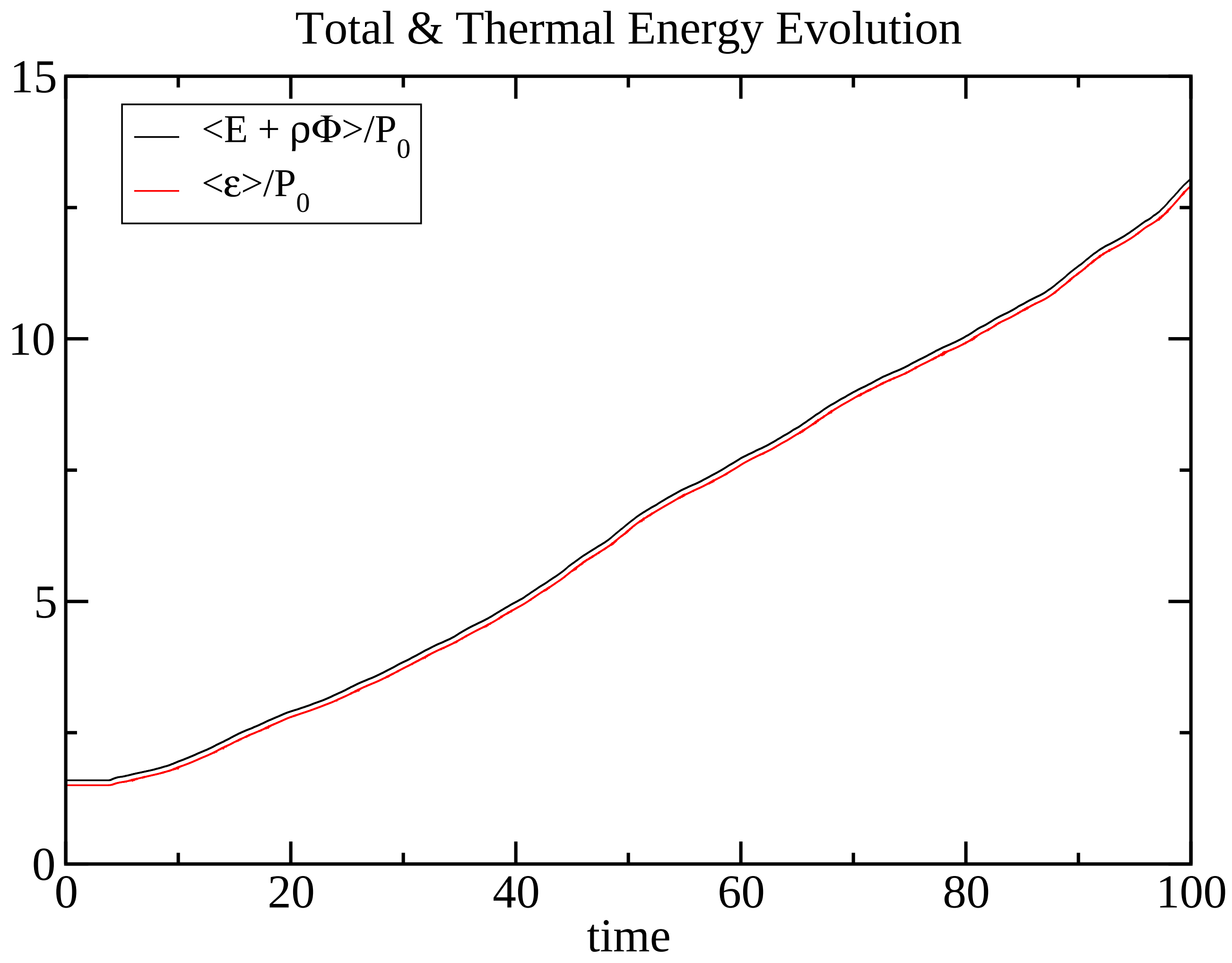
Angular momentum transport due to MTI in rigidly-rotating plasma. Further work, as done by Lesur and Longaretti (2005), at high Reynolds numbers and marginal MTI stability, may be neccesary.

Isotropizing Gyrokinetic Instabilities



Density histogram of measurements of the solar wind by the WIND tele-scope, and is taken from Hellinger et al. (2006).

Necessity of Global Simulations



Secular increase of total energy within a radial slice for simulation of the MRI. Figure taken from Gardiner and Stone (2005).

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